4.1 Groundwater

Groundwater is an important nutrient source to Lake Tahoe. Groundwater with its nutrient load reaches Lake Tahoe when rainfall and snowmelt infiltrate the upland basin, fill deposits and fractured rock and travel down-gradient toward the lake. The groundwater may become enriched with soluble nutrients as it mixes with groundwater that has infiltrated through subsurface areas in both developed and undeveloped land-uses. Ultimately, this groundwater flow is discharged to Lake Tahoe directly or via interflow to tributaries and/or is lost to the atmosphere by evapotranspiration. Nutrient loading from groundwater by streamflow is included in Section 4.3 as part of the upland source analysis. This section focuses on groundwater loading resulting from direct groundwater discharge into Lake Tahoe at the aquifer-lake interface.

A study of the groundwater quality in three major aquifers in the Lake Tahoe basin (Ward Creek, Upper Truckee River, and Trout Creek) (Loeb 1987) concluded that groundwater became enriched with nutrients as it moved toward Lake Tahoe through developed regions of the watersheds. Potential sources of nutrients in groundwater are residual effluent from past sewage disposal sites, fertilizer, effluent from leaky sewage conveyance lines, and infiltrating urban stormwater runoff. The degradation or retardation of nutrients as groundwater flows towards the lake can occur as a result of physical, chemical and biological processes within the aquifer. Groundwater is not considered a source of sediment loading to Lake Tahoe (Tyler 2003 personal communication, Fogg 2003 personal communication).

To better understand groundwater processes and nutrient loading to Lake Tahoe, the USACE completed the *Lake Tahoe Basin Framework Study Groundwater Evaluation* (USACE 2003) in support of TMDL development. This study refined estimates of nitrogen and phosphorus loading from this source. The USACE's Groundwater Evaluation (2003) is the primary information source for this portion of the report.

4.1.1 Groundwater as a Pollutant Source

Thodal (1997) reported that nitrogen and phosphorus loading via groundwater accounted for approximately 15 and 10 percent, respectively, of the overall nutrient loading to the lake. Nitrate (NO_3^-) is the primary form of nitrogen that leaches into groundwater (Follett 1995). Nitrate is highly soluble and moves freely through most soils. Nitrate is repelled by negatively charged clay surfaces, causing it to mobilize rather than attach to soils. Consequently, nitrate travels at the same rate as groundwater flow. Soluble reactive phosphorus (SRP) moves much more slowly, as it is easily taken up by plants and adsorbed to soil particle surfaces (Sharpley 1995).

Groundwater nutrients can affect the water quality of tributary streams. A recent USGS study (Rowe and Allander 2000) found that the Upper Truckee River and Trout Creek supply about 40 percent of all water that flows into Lake Tahoe and that 40 percent of the Upper Truckee River's flow is derived from shallow groundwater. Watershed modeling completed as part of the Lake Tahoe TMDL development indicates even greater percentages of groundwater contribution to tributary flows. The contribution of this very shallow groundwater flow into the tributaries is included as part of the calculations for watershed stream loading. This current section on groundwater focuses on loading from deeper aquifers that discharge directly into Lake Tahoe through the under-water slope faces.

4.1.2 Existing Groundwater Information at Lake Tahoe

Early studies of hydrogeology in the Lake Tahoe basin include McGauhey et al. (1963), Crippen and Pavelka (1970), and Loeb and Goldman (1979). Loeb and Goldman (1979) estimated the total groundwater flow from the Ward Creek watershed into Lake Tahoe from basic hydraulic principles. Later, Loeb (1987) investigated groundwater flow and groundwater quality in the Ward Creek, Upper Truckee River, and Trout Creek aquifers. These studies suggested groundwater nutrient loading in the Ward Creek watershed accounted for 60 percent of the total Dissolved Inorganic Nitrogen (DIN) loading and 45 percent of the watershed's total dissolved phosphorus loading. Woodling (1987) and Loeb (1987) investigated the hydrogeologic aspects of groundwater and lake interactions in the southern portion of the Lake Tahoe basin. They concluded that groundwater loading of DIN from the Upper Truckee-Trout Creek drainage accounted for only 5-20 percent of the total loading from both groundwater and tributaries. The contribution of groundwater to total watershed loading of soluble phosphorus was also low at 2 percent. Ramsing (2000) focused on measuring groundwater seepage into Lake Tahoe. In estimating nutrient transport from the Incline Creek watershed, Ramsing reported DIN from groundwater to be 14 percent of the total watershed budget; while the contribution of soluble phosphorus was insignificant.

The differing nutrient contributions noted in these studies highlight that groundwater aquifers in different regions of the basin do not all behave identically and any comprehensive evaluation of groundwater nutrient loading must account for regional differences.

Thodal (1997) published the first basin-wide evaluation of groundwater quality and quantity from 1990 to 1992. This study established a monitoring network of 32 sample sites that provided information about the relative significance of groundwater to the nutrient budget of Lake Tahoe. Nitrate represented 85 percent of the total nitrogen, ammonia represented 5 percent and organic nitrogen represented 10 percent. The distribution of mean phosphorus concentration was about 55 percent ortho-phosphorus and 42 percent organic phosphorus. Phosphorus was the only constituent found to be statistically different between the fall and spring seasons.

Thodal's 1997 study also includes detailed evaluations of hydraulic gradient, hydraulic conductivity, and recharge-precipitation relationships. Based on these assessments, Thodal estimated annual groundwater contributions directly to the lake for nitrogen and phosphorus were 54 metric tons (metric ton = 1,000 kg) and 3.6 metric tons, respectively.

4.1.3 New Information – Groundwater Evaluation Report

The Groundwater Evaluation conducted by the USACE (2003) serves as an independent assessment of Thodal's (1997) analysis. The 2003 report differs from Thodal's 1997 report in that it divides the basin into geographic regions, rather than providing a single basin-wide value for groundwater loading. Data collected by the USGS and other entities were used to update Thodal's nutrient loading evaluation. In addition, sufficient data were available to develop a groundwater flow model for the South Lake Tahoe area and provide better estimates of groundwater discharge from this region. The USACE groundwater evaluation also provided the contribution of background nutrients to Lake Tahoe. Background loading represents the nutrient flux in groundwater from undisturbed areas.

Delineation of Major Aquifer Limits

The USACE (2003) report divided the Lake Tahoe basin study area into five main regions based on jurisdictional boundaries and major aquifer limits. The five major regions included South Lake Tahoe/Stateline, East Shore, Incline Village, Tahoe Vista/Kings Beach and Tahoe City/West Shore (Figure 4-4). The South Lake Tahoe/Stateline region was further divided into six subregions extending from Emerald Bay to Stateline (Figure 4-5).

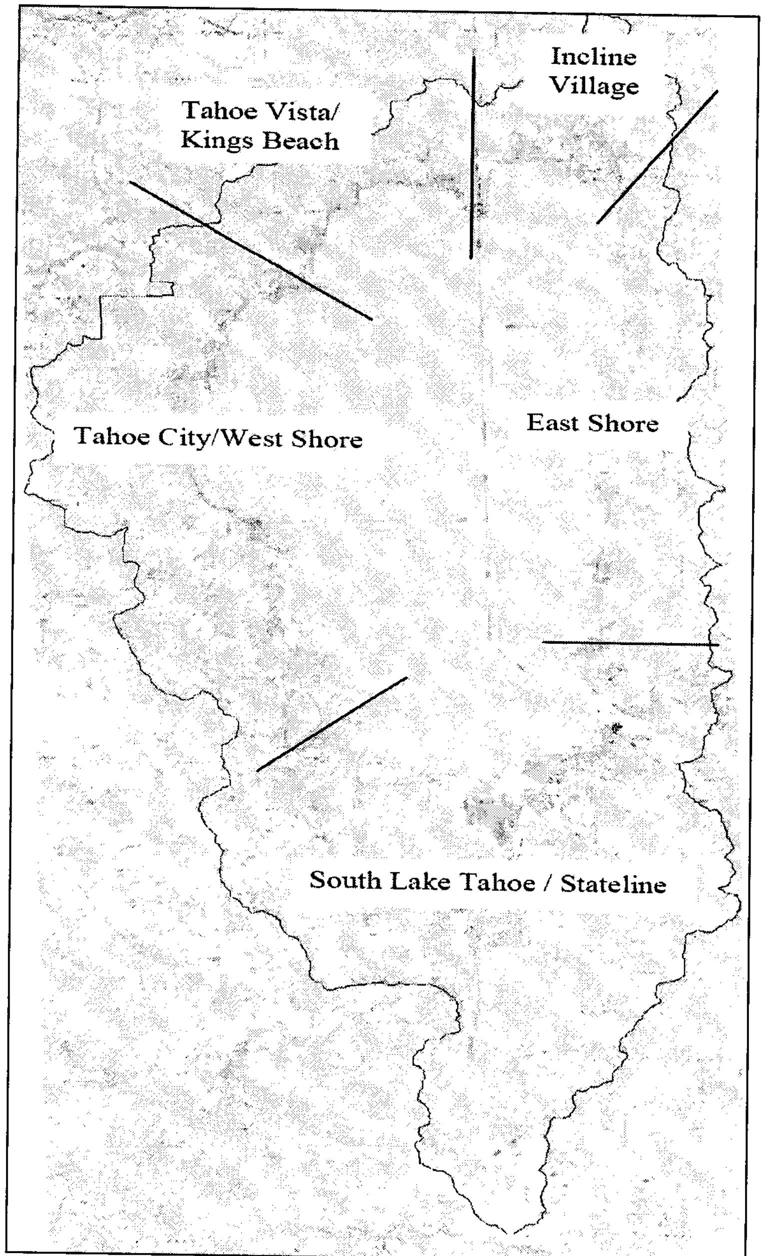

Figure 4-4. Five groundwater evaluation regions in the Lake Tahoe basin (USACE 2003).

Both data collection and a literature review were conducted for the groundwater evaluation. Existing data were obtained for 219 wells from a number of federal, local, and State agencies in California and Nevada. Some data necessary to fully evaluate regional groundwater flow still do not exist. The USACE 2003 report details the sources of data used in that evaluation.

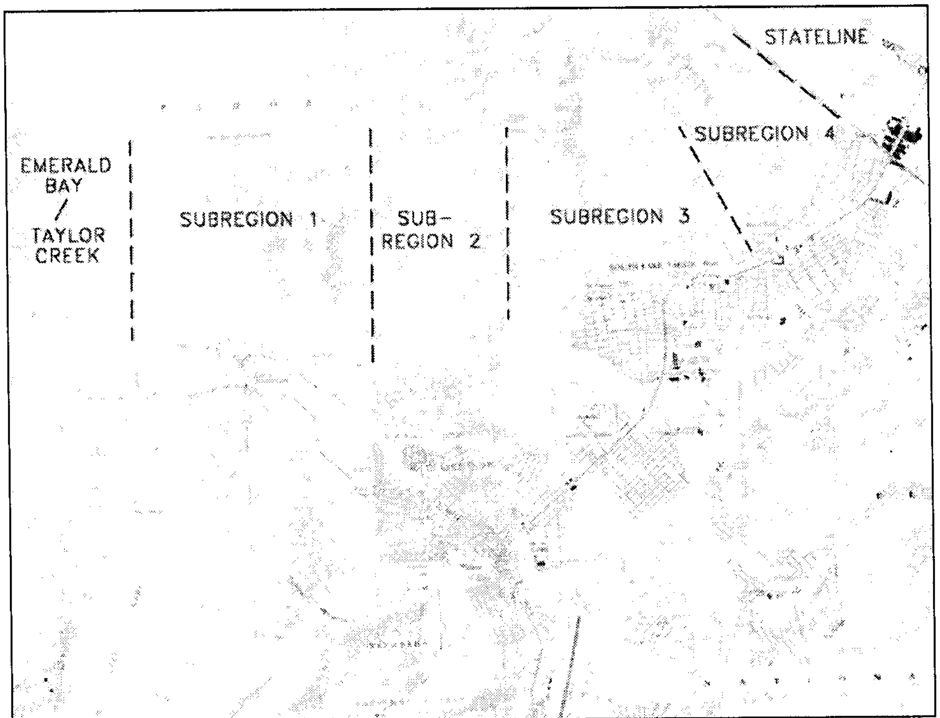

Figure 4-5.The six subregions of the South Lake Tahoe/Stateline region of the Lake Tahoe basin (USACE 2003).

Nutrient Loading Methodology and Estimates

Groundwater discharge for the South Lake Tahoe region was estimated using numerical modeling (Fenske 2003) while Darcy's Law principles were applied to estimate groundwater discharges from other regions.

In applying Darcy's Law, the USACE predicted an average hydraulic conductivity for each region, and then estimated aquifer cross sectional area and hydraulic gradient to calculate flow. Average hydraulic conductivity was estimated from available drill logs. Each well log was partitioned into stratified units and each unit assigned a hydraulic conductivity range, based on published values for similar subsurface material. In some areas, such as portions of the East Shore, few well logs were available and geologic maps and aerial photographs were used to infer subsurface conditions. Aquifer depths were estimated from well logs in proximity to the shoreline and stratigraphic interpretation from geologic maps and aerial photographs. Aquifer lengths were estimated from the bedrock outcrops along the shoreline portrayed in aerial photographs and geologic maps. The lengths of the aquifers were measured from topographic maps.

Using Darcy's Law, the USACE assumed no water is added to or taken away from the system and the aquifer is homogeneous. This simplified approach can give a reasonable estimation of groundwater flow. While it is known that the aquifers in the basin are not homogeneous, the USACE Groundwater Evaluation considered the

Darcy's Law approach to be the most reasonable method to obtain estimated groundwater flow given the lack of available well data.

The USACE estimated groundwater nutrient loads by multiplying estimated flow (volume per time) by nutrient concentration (mass per volume). The nutrient evaluation included: dissolved ammonia + organic nitrogen (dissolved TKN), dissolved nitrate including nitrite, total dissolved nitrogen (TKN + nitrate), dissolved ortho-phosphorus and total dissolved phosphorus (including ortho-phosphorus, organic phosphorus and hydrolyzable phosphorus).

The USACE selected nutrient concentrations by one of the following approaches: (1) average concentration, (2) downgradient concentration, or (3) land-use weighted concentration. The ultimate selection was based on data availability and best professional judgment, each approach is briefly described below.

The average concentration method takes into consideration monitoring data collected from all wells in a region. The average dissolved nitrogen and dissolved phosphorus concentrations were calculated for the cluster of wells located in each region.

The downgradient concentration method takes advantage of groundwater monitoring data collected from wells close to the lake and should reflect groundwater nutrient concentrations expected to reach the lake. This method was used in each area where wells were located near the lake and represented the major upgradient land-uses. The average dissolved nitrogen and dissolved phosphorus concentrations were determined for these downgradient wells only. The nutrient concentrations in the downgradient wells can be used to evaluate whether attenuation is occurring or, conversely, if nutrients are accumulating. This method did not take into account the depth of the aquifer monitored.

The land-use weighted concentration method considers the type of development in the well vicinity. This method was used for areas that did not have groundwater wells. Average nutrient concentrations were calculated from all the basin-wide data then categorized by land-use. The study authors then evaluated each groundwater region using GIS to determine area land-uses. The average nutrient concentrations were then applied to appropriate land-use categories to estimate average groundwater nutrient loads. In cases where land-use types had no associated groundwater quality data, assumptions based on best professional judgment were made by the USACE (2003) report scientists on how specific land-use types affect nutrient loading.

The primary land-uses of concern in the USACE Groundwater Evaluation were residential, commercial and recreational as these land-use types can be sources of nutrients to the groundwater system (USACE 2003). Residential and commercial land-use includes nutrient input from fertilization, stormwater infiltration, leaking sewage lines and/or inactive septic tanks. The primary nutrient source in the typical recreational land-uses is fertilization, although leaking sewage systems may also be in these areas. Because many of the regions did not have adequate monitoring networks at the time of the study, basin-wide average concentrations for specific land-use types were developed. For this analysis, each of the wells located in the Lake Tahoe basin was assigned a land-use code based on its location and basin-wide concentrations for four land-use types were determined by compiling and averaging the analytical results for all wells of the same land-use code (Table 4-4). These values were used for nutrient concentration when the land-use weighted concentration method was employed.

Table 4-4. Average nutrient concentrations of groundwater wells based on land-use types (USACE 2003).

Land-use	Nitrogen Ammonia + Organic Dissolved (mg/L)	Nitrogen Nitrite plus Nitrate Dissolved (mg/L)	Total Dissolved Nitrogen (mg/L)	Dissolved Orthophosphorus (mg/L)	Total Dissolved Phosphorus (mg/L)
Residential	0.26	0.37	0.63	0.081	0.11
Commercial	0.16	0.51	0.67	0.092	0.12
Recreational	0.40	1.2	1.6	0.073	0.10
Background	0.16	0.11	0.27	0.040	0.049

Background conditions represent the concentration of nutrients that would be naturally occurring in the groundwater without the added impact of human development. It was assumed that these conditions were best represented by nutrient concentrations observed in undeveloped and undisturbed areas (vegetated and forested).

Subregional Flow and Nutrient Loading

The USACE developed regional groundwater discharge and nutrient loading estimates throughout the basin. Each of the major groundwater regions has unique characteristics that warranted region-specific nutrient loading estimates. These regional values were combined to evaluate the overall estimates of groundwater nutrient loading to Lake Tahoe. Table 4-5 provides a range of loading values and an estimate of what is considered a reasonable loading value for groundwater in each area.

The loading percentage estimates at the bottom of Table 4-5 are presented on a regional basis. The contribution of both nitrogen and phosphorus from the South Lake Tahoe/Stateline region was less than five percent of the basin-wide total. The shallow hydraulic slope on the South Shore and aquifer pumping in this region are the main factors in the lower groundwater discharge rate in the South Shore/Stateline area.

Table 4-5. Subregional Groundwater Loading Estimates (USACE 2003).

Constituent		Region										Total Groundwater Loading to Lake Tahoe
		South Lake Tahoe/Stateline						Incline Village	Tahoe Vista/Kings Beach	Tahoe City/West Shore	East Shore	
		Emerald Bay to Taylor Creek	Subregion 1	Subregion 2	Subregion 3	Subregion 4	Stateline					
Dissolved Ammonia + Organic (kg/yr)	Min	10	110	11	0	86	180	200	1,700	1,400	1,300	
	Max	130	710	330	20	460	550	2,100	6,400	17,000	2,300	
	Estimate	70	340	250	9	170	550	1,600	2,700	9,800	2,300	
Average Concentration (mg/L)		0.045	0.71	0.21	0.19	0.23	0.64	0.24	0.27	0.26	0.47	
Dissolved Nitrate (kg/yr)	Min	10	12	92	0	15	34	400	1,600	1,300	1,800	
	Max	140	64	1,100	68	650	840	11,000	8,600	31,000	3,900	
	Estimate	80	30	530	13	290	95	2,600	6,800	18,000	3,900	
Average Concentration (mg/L)		0.051	0.057	0.44	0.26	0.40	0.11	0.39	0.70	0.47	0.81	
Total Dissolved Nitrogen (kg/yr)	Min	20	130	100	1	230	370	60	4,800	2,700	3,100	12,000
	Max	270	770	1,300	80	1,300	1,200	13,000	15,000	48,000	6,200	87,000
	Estimate	150	370	780	22	450	650	4,200	9,400	28,000	6,200	50,000
Average Concentration (mg/L)		0.096	0.77	0.65	0.45	0.63	0.75	0.63	0.97	0.73	1.28	
Dissolved Orthophosphate (kg/yr)	Min	20	8	4	0	24	7	6	390	1,000	500	
	Max	200	43	140	10	72	17	720	1,300	5,400	1,100	
	Estimate	110	15	100	3	60	17	550	820	3,100	900	
Average Concentration (mg/l)		0.071	0.032	0.086	0.062	0.084	0.020	0.082	0.084	0.082	0.019	
Total Dissolved Phosphorus (kg/yr)	Min	20	11	7	0	19	11	10	670	1,500	80	2,400
	Max	240	59	190	10	100	30	1,000	2,200	7,600	150	12,000
	Estimate	140	28	140	4	83	30	770	1,100	4,400	140	6,800
Average Concentration (mg/L)		0.085	0.055	0.12	0.083	0.12	0.034	0.12	0.11	0.11	0.029	
Discharge Rate (m^3/yr)	Min	250,000	230,000	250,000	1,200	370,000	490,000	99,000	6,400,000	14,000,000	2,700,000	
	Max	2,800,000	990,000	1,600,000	120,000	860,000	860,000	8,800,000	9,700,000	66,000,000	4,800,000	
	Estimate	1,600,000	470,000	1,200,000	49,000	720,000	860,000	6,700,000	9,700,000	38,000,000	4,800,000	
% of Total Groundwater Total Dissolved Nitrogen Loading		0.30%	0.74%	1.56%	0.04%	0.90%	1.30%	8.40%	18.80%	56.00%	12.40%	
% of Total Groundwater Total Dissolved Phosphorus Loading		2.06%	0.41%	2.06%	0.06%	1.23%	0.44%	11.32%	16.18%	64.71%	2.06%	

4.1.4 Basin-wide Flow and Nutrient Loading from Groundwater

The USACE estimated total dissolved nitrogen and total dissolved phosphorus loading to Lake Tahoe from groundwater to be approximately 50,000 kg/yr and 6,800 kg/yr, respectively. These estimates were very similar to those of Thodal (1997) (Table 4-6). Estimated basin-wide groundwater volume discharge to Lake Tahoe ranged from 4.9×10^7 m^3/yr to 6.4×10^7 m^3/yr. Fogg (2002) estimated a similar value for basin-wide ground water flow into Lake Tahoe (3.7×10^7 m^3/yr).

Table 4-6. Basin-wide nutrient loading and groundwater discharge estimates (USACE 2003).

Constituent	USACE 2003	Thodal 1997
Total Dissolved Nitrogen (kg/yr)	50,000	60,000
Total Dissolved Phosphorus (kg/yr)	6,800	4,000
Discharge Rate (m^3/yr)	6.4×10^7	4.9×10^7

The methods used to develop the discharge rates and ultimately nutrient loading are inherently uncertain. This uncertainty is discussed in more detail in the Thodal (1997) and USACE (2003) reports. While there may be the potential for error using the methods presented, the similarity between independent analysis supports the discharge estimates. On the basis of these findings, the mean of the Thodal (1997) and USACE (2003) studies were used as inputs to the Lake Clarity Model as part of the TMDL Linkage Analysis.

Generally, the highest loading comes from the west shore aquifers. These loads are high primarily because the groundwater discharge rate is the highest of all subregions.

Background Nutrient Loading to Lake Tahoe from Groundwater

Natural groundwater nutrient loading estimates were provided in the USACE (2003) Groundwater Evaluation report. These estimates do not signify if a well in a relatively undisturbed location may be influenced by a possible upgradient source in an urbanized area. Annual background loads for total dissolved nitrogen and total dissolved phosphorus from the different regions are provided in Table 4-7. The estimated background groundwater nutrient loading to Lake Tahoe represents approximately 46 percent and 34 percent of the phosphorus and nitrogen loading, respectively. This suggests anthropogenic sources are more likely to influence subsurface nitrogen concentrations more than phosphorus levels.

Table 4-7. Background groundwater nutrient loading to Lake Tahoe by region (USACE 2003).

Constituent	Region										Total Groundwater Loading to Lake Tahoe
	South Lake Tahoe / Stateline						Incline Village	Tahoe Vista / Kings Beach	Tahoe City / West Shore	East Shore	
	Emerald Bay to Taylor Creek	Sub-region 1	Sub-region 2	Sub-region 3	Sub-region 4	State-line					
Average Background Total Dissolved Nitrogen (kg/yr)	150	127	330	13	190	230	1,800	2,600	10,390	1,300	17,000
Average Background Total Dissolved Phosphorus (kg/yr)	80	23	59	2	35	30	330	480	1,890	140	3,100

4.1.5 Groundwater Nutrient Sources

This section identifies the known and potential nitrogen and phosphorus sources to groundwater and is integral in determining ground water load reduction alternatives. The key sources evaluated include fertilized areas, sewage, infiltration basins, and urban infiltration. It is important to note there are insufficient data and scientific understanding at this time to directly link these sources to the estimated groundwater nutrient load values presented above. Rather than make a direct correlation between potential sources and groundwater quality, this section provides information on those sources that might be contributing to groundwater nutrient pollution. For example, while fertilizer application rates can be estimated, there is no information on the relative contribution of nitrogen fertilizer in the estimated 50 metric ton basin-wide groundwater nitrogen loading value. Nutrients are also present in the natural system and will contribute to the concentrations in groundwater. There are certain research techniques that could be promising in this regard (e.g., stable isotope tracing, chemical fingerprinting). However, there are currently no comprehensive, field-based measurements that quantify the amount of nutrients from trace fertilizer, sewer line exfiltration or urban infiltration that directly enter the lake by groundwater.

Fertilizer

Fertilizer use has received increasing attention as a potential source of nutrient loading to Lake Tahoe. Historical fertilizer use in the Lake Tahoe basin has not be comprehensively documented and, more importantly, not well understood in terms of nutrient flux to the lake. In 1972, Mitchell and Reisnauer conducted what is considered the first survey to assess fertilizer use in the Lake Tahoe area. He found the principal areas of fertilizer use in the Lake Tahoe basin were golf courses, school grounds, and landscaped areas around motels, condominiums and permanent resident homes. This report also estimated fertilizer use by homeowners from application instructions and land areas. Mitchell and Reisnauer (1972) reported that fertilizer use added approximately 48 metric tons of nitrogen and 7 metric tons of phosphorus to the basin annually. Approximately a decade later, Loeb (1986) estimated that topical application of fertilizer added 79.3 – 84.6 metric tons of nitrogen and 26.4 – 28.2 metric tons of phosphorus into the Tahoe basin. Other than providing a quantity range for fertilizer nutrient loading to the entire Lake Tahoe basin, Loeb (1986) supplied no other details concerning fertilizer application nor was a reference provided for the quantity information.

In the USACE (2003) Groundwater Evaluation, fertilized areas were broken down into residential neighborhoods, recreational facilities, institutional sources, commercial sources and livestock/agriculture. Residential and recreational sources were assumed to be the most significant in the basin as livestock/agriculture is very limited and commercial and institutional sources are typically small, improved areas covered largely by impervious surfaces. Residential neighborhoods consist of both single family and multi-family homes. The *Home Landscaping Guide for Lake Tahoe and Vicinity* (UNR 2001) was used to evaluate potential loading from residential neighborhoods. A scenario using "off the shelf" fertilizers was also considered as a "worst case" loading estimate. Recreational facilities were separated into golf courses and urban parks. The loading estimates from these two sources are based on fertilizer management plans developed for several golf courses and communication with local Public Utility Districts. Institutions consisted of schools, cemeteries and all other institutional establishments. Commercial and agricultural land-uses were not categorized into more specific regions.

To quantify the amount of fertilizer applied in the Lake Tahoe basin, several steps were taken. First, the USACE designated several area categories based on land-use (TRG 2002) and potential for fertilization. Since only a portion of each land-use area receives fertilizers, the area fertilized in each land-use category was determined or estimated. The method for determining the percent fertilized land area for each category was based on historical reports (Mitchell and Reisnauer 1972) and best professional judgment. Next, typical fertilizer application rates were applied according to land-use. From the loading rate and the land area of application values, the mass of fertilizer applied was then determined. Finally, the loading rates for single-family homes and golf greens were applied to a simplified phosphorus leaching model to determine the amount of phosphorus available for leaching into groundwater. Single-family home areas and golf greens were specifically modeled because of their potential to include both regular watering and fertilizer application. Refer to Chapter 10 in the USACE (2003) Groundwater Evaluation report for more details associated with these nutrient loading estimates and the phosphorus leaching model. Table 4-8 presents the resulting fertilized areas.

Table 4-8. Fertilized areas in the Lake Tahoe basin (USACE 2003).

Land-use Category	Specific Use	Land Area (km^2)	Percent of Area Estimated to be Fertilized (%)	Area Fertilized (km^2)
Residential	General	0.021	20	0.0045
	Single-family Residential	45	21	9.4
	Multi-family Residential	13	20	2.7
	Subtotal	59		12
Recreational	Golf Courses	4	95	3.8
	Urban Parks	0.29	50	0.14
	Subtotal	4.3		3.9
Institutions	General	2	20	0.41
	Schools	0.88	50	0.44
	Cemeteries	0.015	95	0.014
	Subtotal	2.9		0.86
Commercial	Commercial	18	10	1.8
Agriculture	Agriculture/ Livestock	0.54	100	0.54
Total		**84**		**19**

Current fertilizer application rates as calculated by the USACE (2003) are much higher than estimates determined in 1972 (Table 4-9). Based on the USACE estimates, the annual soil loading of nitrogen in the Lake Tahoe basin has potentially tripled from approximately 48 metric tons in 1972 to a range of 143-295 metric tons today. The potential annual soil loading of phosphorus has increased from approximately 7 metric tons in 1972 to at least 45 metric tons or even higher today. The range of phosphorus addition due to fertilizer application ranged from 45 to 429 metric tons per year. Even at the recommended application rates, the potential amount of fertilizer applied by individual property owners is large. While the USACE (2003) Groundwater Evaluation report liberally assigned fertilizer use to a portion of the land area of all single-family homeowners in the Lake Tahoe basin, the values from the remaining land-use areas were considered by the USACE authors to be based on realistic rates. When considering only the application rates from recreational, institutional and commercial areas, nitrogen application may have increased roughly 230 percent while phosphorus use has increased over 400 percent. Note the highest degree of uncertainty associated with the USACE (2003) estimates is associated with fertilizer use in the residential land-use category.

Sewage Exfiltration and Abandoned Septic Tanks

Another potential source of groundwater nutrient pollution may be active sewage line exfiltration or residual contamination from abandoned septic tanks and treated sewage infiltration areas. Exfiltration is the incidental outflow, or leakage, from sewer collection/flow pipes due to joints, cracks, holes or breaks in the pipe. Collection systems are typically designed to account for a certain amount of leakage (e.g., average new construction allowable leakage rates range from 90 to 280 liters/day/cm-diameter/kilometer (100 to 300 gallons/day/inch-diameter/mile) of pipe).

A study conducted by Camp Dresser and McKee (CDM 2002) for the USACE (2003) concluded that exfiltration did not appear to be a major source of nutrients to Lake Tahoe when compared to all sources.

Table 4-9. Estimated annual nitrogen and phosphorus application rates in the Lake Tahoe basin in 1972 (Mitchell and Reisnauer 1972) versus the application rate estimated for recent conditions by the USACE (2003). The load presented in the column labeled 2003 is best considered as an estimate over the period 2000-2003. (USACE 2003)

Land-use Category	Specific Use	Metric Tons of Nitrogen		Metric Tons of Phosphorus	
		1972	2003	1972	2003
Residential	General	-	0.027	-	0.009
	Single-family Residential	-	49.1-200.6	-	17.1-401
	Multi-familiy Residential	-	14.4	-	5.1
	Subtotal	13.6	64-215	1	22.2-406
Recreational	Golf Courses	26	51.8	4	16.7
	Urban Parks		2		0.27
	Subtotal	26	53.8	4	17
Institutions	General		5.8		0.8
	Schools	1.8	6.2	<0.36	0.9
	Cemeteries		0.18		0.027
	Subtotal	1.8	12.2	<0.36	1.7
Commercial	Commercial	2.3	8.9	<0.36	3.1
	Subtotal	2.3	8.9	<0.36	3.1
Agriculture	Agriculture/ Livestock	4.5	4.5	0.9	0.9
	Subtotal	4.5	4.5	0.9	0.9
Total		~48	143-294	~7	45-429

Infiltration Basins and Urban Infiltration

Infiltration basins and urban infiltration can also contribute nutrients to groundwater. Infiltration basins are constructed specifically to collect stormwater runoff and allow it to slowly percolate into the groundwater aquifer(s) below. These basins are intended to prevent untreated nutrient loads from directly entering the lake via sheet flow or storm drainage outfalls, and to prevent concentrated nutrient loads from entering streams that flow into the lake.

A 2006 study by 2NDNATURE provided a synthesis of existing research on performance of dry detention basins, constructed wetlands, and mechanical treatment structures in the Lake Tahoe basin. The study found that typical Tahoe urban stormwater poses little risk of migrating hydrophobic hydrocarbons into the underlying groundwater from the detention or infiltration facilities provided there is adequate separation between the underlying soils and the groundwater surface. From a limited nutrient sampling, analyses suggest that a nitrate plume may pulse into shallow groundwater from dry detention basins during spring snow melt conditions.

4.2 Shoreline Erosion

Lake Tahoe's shoreline is a dynamic environment where wave action and lake level fluctuation are dominant forces. Many shoreline sections can change shape on an annual basis as sediment is eroded, transported and deposited. Depending on location along the shoreline, these processes occur at different rates. Figure 4-6 shows fallen trees, which is evidence of relatively recent shoreline erosion. Waves in the nearshore area also help redistribute eroded sediment. Prior to 2000, the extent of shoreline erosion had been roughly estimated (Reuter and Miller 2000) but did not adequately quantify nutrient and sediment loading.

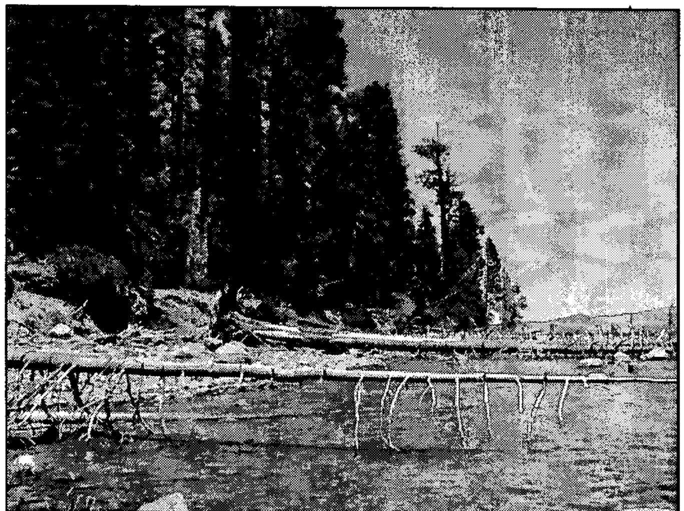

Figure 4-6. Photograph looking north at Sugar Pine Point State Park (Adams 2004).

This section of the report summarizes a detailed study performed by researchers with the Desert Research Institute that incorporated georectified historical air photos into a GIS database combined with field observations and nutrient sampling to determine the amount and processes affecting nitrogen, phosphorus and sediment inputs to Lake Tahoe from shoreline sources (Adams and Minor 2001). A supplementary analysis of particle size distributions of Lake Tahoe shorezone sediment was also included in *Shorezone Erosion at Lake Tahoe: Historical Aspects, Processes, and Stochastic Modeling* (Adams 2004).

The research team acquired historic aerial photographs and digital orthophotographic quadrangles (DOQs) spanning a 60-year time frame (1938-1998) from the TRPA, the United States Forest Service Lake Tahoe Basin Management Unit (USFS LTBMU), and the USGS, respectively. This data was available for 1938, 1939, 1940, 1952, 1992, 1995 and 1998 with aerial photographs of the entire basin taken in 1992 and 1998. Almost all the shoreline was mapped from the 1938-1940 images. The images were scanned and rectified using ground control points common to both the aerial photographs and the USGS DOQs. By calculating the relative measure of accuracy between the predicted and observed control point locations, spatial error between photographic and map data was estimated to be with within two meters. These calculated accuracy values exceed National Mapping Accuracy Standards (USGS 1941).

After the maps and photographs were digitally scanned and rectified, the former shoreline position was delineated based on consistent observable shoreline features. During the 1990s, Lake Tahoe experienced the most dramatic lake-level changes in recorded history, fluctuating between its historic low of 6,220.26 feet in late 1992 to a high of approximately 3.5 inches above the legal limit (6,229.1 feet) in early January 1997 (Boughton et al. 1997). Since the result of lake level fluctuations is an apparent shoreline migration (Adams and Minor 2001), the research team made corrections so that their analysis reflected actual changes to the shoreline configuration with no interference resulting from lake level changes.

Since the aerial photographs literally only provide a 'snapshot in time', and based on the assumption that most shoreline change likely happens when the lake is at or near its legal limit, the research team devised a technique to estimate the position of the shore through time by correcting for different water levels based on the concept that on a stable, sloping shoreline the shore-water interface will migrate laterally in a predictable way depending on water level. Four different situations were noted in comparing the various historical shorelines to the present condition: (1) no change; (2) erosion; (3) accretion; and (4) oscillation. Oscillation is where both erosion and accretion have taken place along this shore over the last 60 years. In each situation (with the exception of an unchanged shoreline), simple trigonometry was used to estimate the amount of net shoreline change. A constant shoreline slope was assumed.

Sediment grab samples were collected from multiple shoreline locations to analyze the nutrient content of the lost shorezone material. Typically, samples were collected from the beach, wave-cut scarps (steep slopes that result from erosion) (Figure 4-7), and in the backshore area from depths ranging from ten centimeters on the beaches to three meters on exposed wave-cut exposures. Samples were analyzed for total phosphorus and total Kjeldahl nitrogen (TKN).

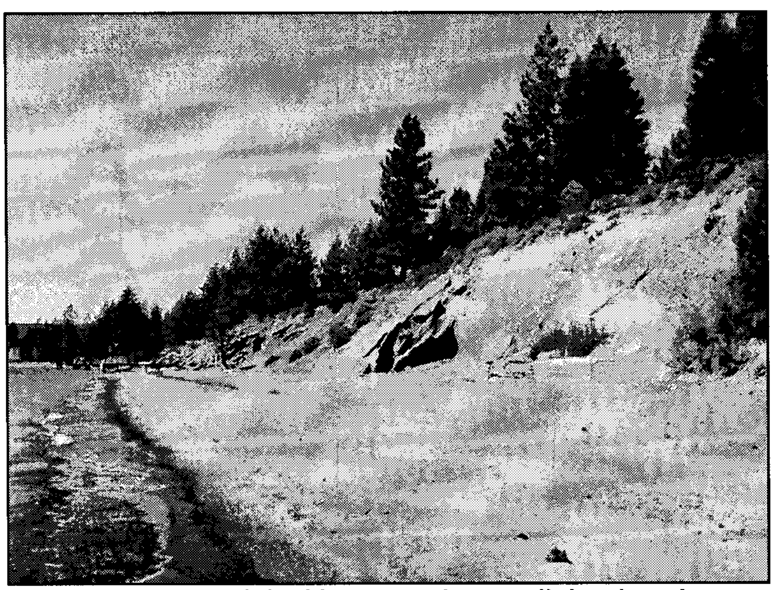

Figure 4-7. Photograph looking west along well-developed wave cut scarp at Lake Forest shoreline.

Study results indicate both shoreline erosion and accretion have occurred over the last 60 years. A total of 22 erosion areas were identified, the largest of which encompasses an area of 32,000 m^2. In calculating the load of sediment and associated nutrients, the research team estimated the thickness of each eroded area using large-scale Bureau of Reclamation topographic maps dating from 1918 and 1919 and assumed a sediment bulk density of 1.5 grams per cubic centimeter. Based on these calculations, the total mass of sediment eroded into Lake Tahoe from the shorezone since 1938 amounts to approximately 429,000 metric tons.

A follow-up study was conducted to assess the particle size distribution of collected shoreline sediment samples (Adams 2004). This work determined that of the 429,000 metric tons of material eroded into the lake, approximately 92 percent of that material is composed of sand-sized sediment (≥ 63 μm), roughly 6 percent was in the silt size fraction (3 – 62.5 μm), with the remaining 2 percent < 3 μm in size. When averaged over the 60 year erosion period, these values equate to about 6,600, 440, and 110 metric tons of sand, silt and clay per year, respectively.

Nutrient analysis of shoreline sediments indicates sediment from around the lakeshore is generally higher in phosphorus than nitrogen. Based on the nutrient sampling data, approximately 117 metric tons of phosphorus and 110 metric tons of nitrogen have been introduced into the lake because of shoreline erosion over the last 60 years. These volumes equate to roughly two metric tons per year of phosphorus and 1.8 metric tons per year of nitrogen. These loading values were used as inputs to the Lake Clarity Model.

4.3 Upland Sources

Upland sources are those that originate from the watershed and are delivered to the lake either by streamflow through one of the 63 major tributaries around the lake or by direct inflow from intervening zones. While the majority of the basin's individual watersheds contain a permanent channel that discharges into Lake Tahoe at a stream mouth, surface runoff in some of these watersheds flows directly to the lake without first entering a channel. These are referred to as intervening zones.

Upland sources include products of anthropogenic influence as well as products of natural surface erosion and groundwater processes. Upland sources include both urban and non-urban (vegetated) land-uses, and the full spectrum of variation within each of these two generalized categories. A watershed model is a tool designed to assist in capturing and assimilating multiple influences to provide spatial and temporal resolution to the science of source characterization. When adequately configured, a watershed model also provides a robust framework for disaggregating and quantifying the relative impact of individual influences or practices (and potential changes to those practices) relative to an established baseline condition. This section describes the development, application, and summary of results for the specific model that was used to characterize upland sources in the Lake Tahoe watershed. Sediment and nutrients that originate in stream channels are considered separately in Section 4.4 since that material is not directly reflective of land-use characteristics in the watershed.

4.3.1 Lake Tahoe Watershed Model Description

This section summarizes the upland source loadings and the watershed model used to determine those loadings. Results from the Lake Tahoe Watershed Model were used as input data (representing watershed inputs) for the Lake Clarity Model as developed by the University of California at Davis (UC Davis). For additional information regarding the watershed model please refer to the modeling report titled *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load* (Tetra Tech 2007).

A watershed model is essentially a series of algorithms that integrate meteorological data and watershed characteristics to simulate upland and tributary routing processes, including hydrology and pollutant transport. Once a model has been adequately set up and calibrated, and the dominant unit processes are deemed representative of monitored conditions, it becomes a useful tool to predict flows and quantify loads from the upland tributaries. Additionally, it can be used to simulate changes in load expected from changes in land-use, and can serve as the platform for estimating basin-wide pollutant reduction resulting from BMP/restoration strategies.

Loading Simulation Program C++ (LSPC) (http://www.epa.gov/athens/wwqtsc/html/lspc.html) was selected to develop the Lake Tahoe Watershed Model. LSPC is a USEPA-approved modeling system that includes Hydrologic Simulation Program – FORTRAN (HSPF) algorithms for simulating watershed hydrology, erosion and water quality processes, as well as in-stream transport processes.

LSPC was developed to facilitate large scale, data intensive watershed modeling applications. A relational Microsoft Access database serves as the framework for watershed data management. A key advantage of the LSPC development framework is that it has no inherent limitations in terms of modeling size or upper limit of model operations imposed by the original FORTRAN architecture. LSPC is currently maintained by the USEPA Office of Research and Development in Athens, Georgia and is a component of USEPA's National TMDL Toolbox (http://www.epa.gov/athens/wwqtsc/index.html). A detailed discussion of HSPF-simulated processes and model parameters is available in the HSPF User's Manual (Bicknell et al. 1997).

4.3.2 Modeling Approach Overview

Usefulness of the Watershed Model

The advantages of choosing LSPC to develop the Lake Tahoe Watershed Model for the Lake Tahoe basin include:

- It simulates the necessary constituents and applies to non-urban and urban watersheds
- Its comprehensive modeling framework can facilitate development of TMDLs not only for this project but also for potential future projects to address other impairments throughout the Lake Tahoe basin
- It allows for customization of algorithms and subroutines to accommodate the particular needs of the Lake Tahoe basin
- The time-variable nature of the modeling will enable a straightforward evaluation of the relationship between source contributions and water body response, as well as direct comparison to relevant water quality criteria
- The proposed modeling tools are in the public domain and approved by USEPA for use in TMDLs
- The model includes both surface runoff and base flow (groundwater) conditions
- It provides storage of all physiographic, point source/withdrawal data and process-based modeling parameters in a Microsoft Access database and text file formats to provide for efficient manipulation of data
- It presents no inherent limitations regarding the size and number of watersheds and streams that can be modeled
- It provides flexible model output options for efficient post-processing and analysis designed specifically to support TMDL development and reporting requirements
- It can be linked to the Lake Tahoe receiving water model (Lake Clarity Model)

How the Tahoe-Specific Model Works

LSPC is a comprehensive watershed and receiving water quality modeling framework. The LSPC framework is developed in a modular fashion with many different components that can be assembled in different ways, depending on the objectives of the individual project. The relevant modules applied for the Lake Tahoe Watershed Model are presented in Table 4-10.

Table 4-10. Description of LSPC modules applied to the Lake Tahoe Watershed Model.

Module	Module Components
LAND – for simulating watershed processes on pervious and impervious land segments	ATEMP / SNOW / WATER – for simulating air temperature/elevation lapse rate, snowfall and snowmelt, and pervious/impervious hydrology
	SEDIMENT – for simulating erosion, production, and removal of sediment and particles from land surfaces
	QUAL – for simulating generalized pollutant generation from surface and subsurface land segments
RCHRES – for simulating processes in streams and vertically mixed lakes	SEDTRN – for simulating in-stream transport, deposition, and scour of sediment
	RQUAL – for simulating in-stream nutrient transformations and transport

The pollutants of concern for the Lake Tahoe TMDL are fine sediment and nutrients (specifically nitrogen and phosphorus.) Fine sediments (particles < 63 μm) are represented as a fraction of the total suspended sediment (TSS) observed in the tributaries. Different potential sources of pollutants are associated with each of the various land-uses in the Lake Tahoe basin and each land-use affects the hydrology of the basin in a different way. Some of these sources contribute relatively constant discharges of pollutants while others are heavily influenced by snowmelt and rain events.

In the Lake Tahoe Watershed Model, a watershed is spatially divided into a series of subwatershed and reach networks. Each subwatershed represents the immediate drainage area for a reach segment. Each subwatershed is further subdivided into land-use segments. For urban developed areas, the land-use segments are further divided into pervious and impervious segments. During a simulation run, the model links the surface runoff and groundwater flow contributions from each of the land segments and subwatersheds and routes them through the network of stream reaches as water moves toward Lake Tahoe. Each stream segment also considers precipitation and evaporation from water surfaces, as well as flow contributions from the watershed, tributaries and upstream stream reaches. The stream network is constructed to represent all of the major tributary streams, as well as different portions of stream reaches where significant changes in water quality occur. Figure 4-8 graphically shows the information/processes that the Lake Tahoe Watershed Model uses to simulate the upland sources to Lake Tahoe.

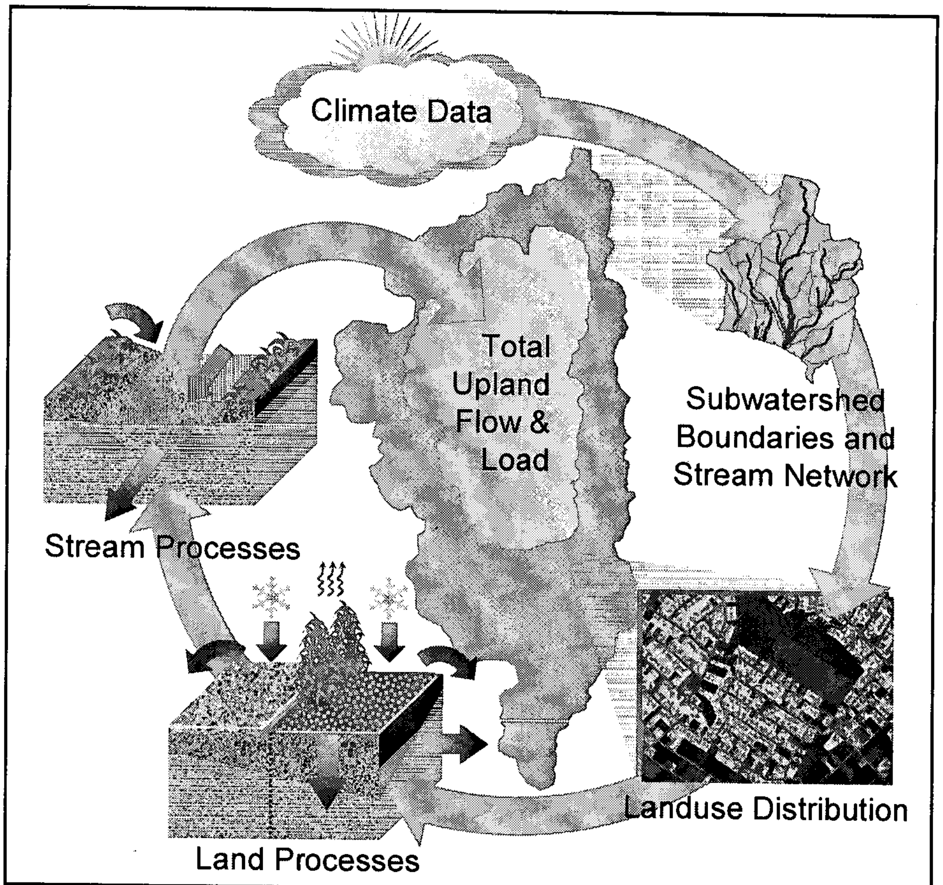

Figure 4-8. Processes simulated by the Lake Tahoe Watershed Model (Tetra Tech 2007).

The Lake Tahoe Watershed Model framework is flexible and allows different combinations of constituents to be modeled depending on data availability and the objectives of the study. Lake Tahoe tributaries are generally fast moving systems which remain well mixed. Therefore, nutrient transport tends to remain relatively conservative. For this approach, a hybrid approach employed to deliver the required nutrient speciation to the Lake Clarity Model. Sediment, total nitrogen and total phosphorus were simulated from land, while observed nutrient distributions were used to partition nutrients into orthophosphate (expressed as soluble reactive-P), organic phosphorus, ammonia, nitrate+nitrite, and organic-N for in-stream transport. No in-stream transformations or biological interactions were simulated given the short duration of transport in the stream channel and to the lake.

4.3.3 Model Set-Up

Developing and applying the Lake Tahoe Watershed Model to address the project objectives involved the following important steps:

1. Watershed segmentation
2. Water body representation
3. Configuration of key model components—meteorological data, land-use representation, and soils

4. Model calibration and validation (for hydrology, sediment, and nutrients)
5. Model simulation for existing conditions and scenarios

Watershed Delineation

The Lake Tahoe Watershed Model was configured to simulate the entire Lake Tahoe basin as a series of hydrologically connected subwatersheds. The delineation of subwatersheds was based primarily on topography, but it also considered spatial variation in sources, hydrology, jurisdictional boundaries, and the location of water quality monitoring and stream flow gauging stations. The spatial division of the watersheds allowed for a more refined resolution of pollutant sources and a more representative description of hydrologic variability.

Representing elevation change in gradual increments was an important consideration for subwatershed delineation since air temperature at a monitoring station is adjusted to mean watershed elevation during snow versus rain simulation. The great variation in topography and land-uses in the Lake Tahoe basin required that the subwatersheds be small enough to minimize these averaging effects and to capture the spatial variability. Lake Tahoe's drainage area was divided into 184 subwatersheds representing 63 direct tributary inputs to the lake. The average size of each subwatershed was 1,100 acres. Figure 4-9 shows the subwatershed delineation for the Lake Tahoe Watershed Model.

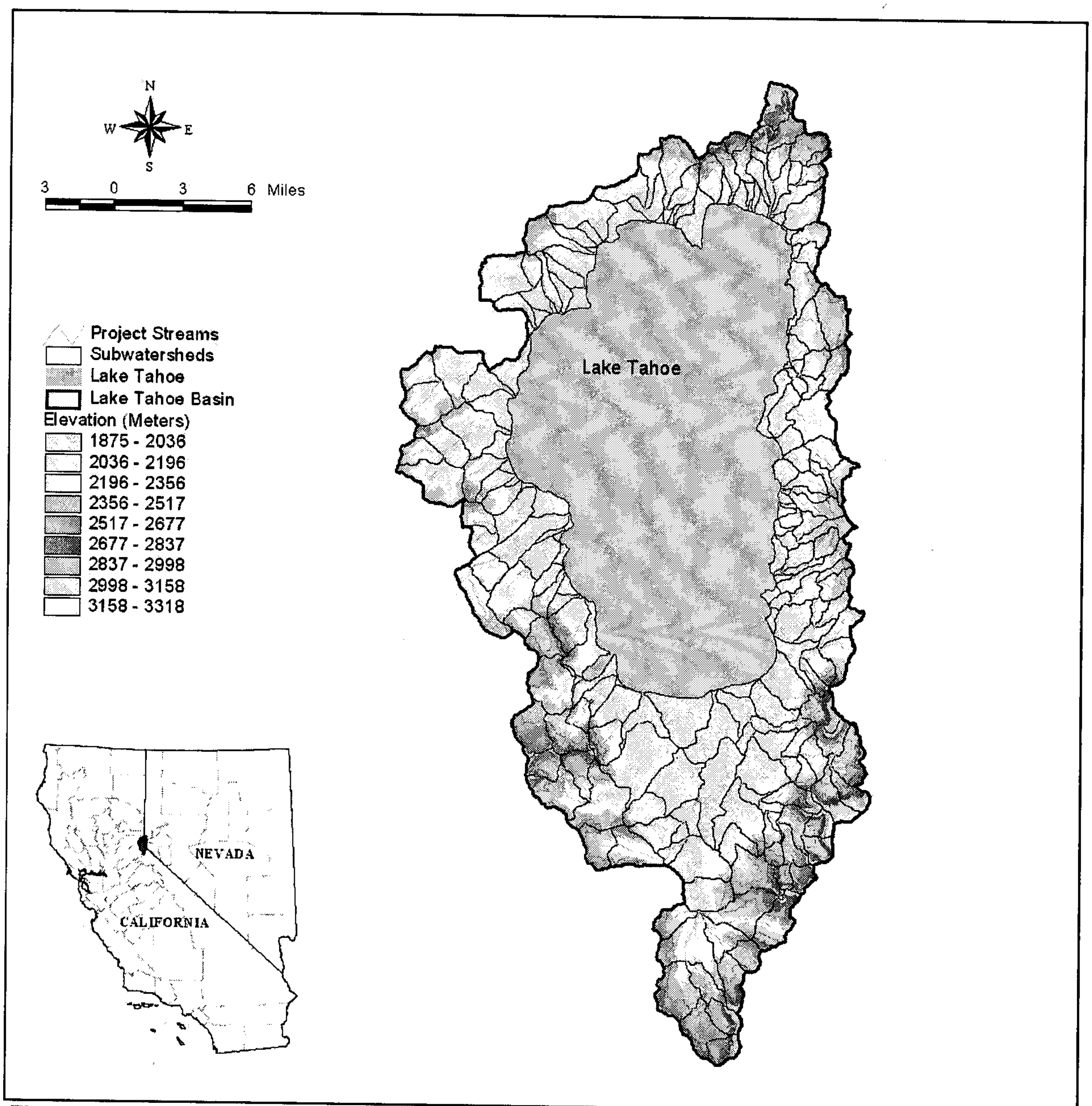

Figure 4-9. Subwatershed delineation and elevation (in meters) (Tetra Tech 2007).

Areas between stream mouths that directly drain into the lake (intervening zones) were modeled separately. The intervening zones represent both urban and forested land-uses. Nine groups of intervening zones were represented in the model as shown in Figure 4-10. The intervening zones were placed into a group corresponding to one of the monitored LTIMP streams based on proximity, similarity of land-use and other considerations, to see which LTIMP stream data was applied, see Table 5-4 (Tetra Tech 2007).

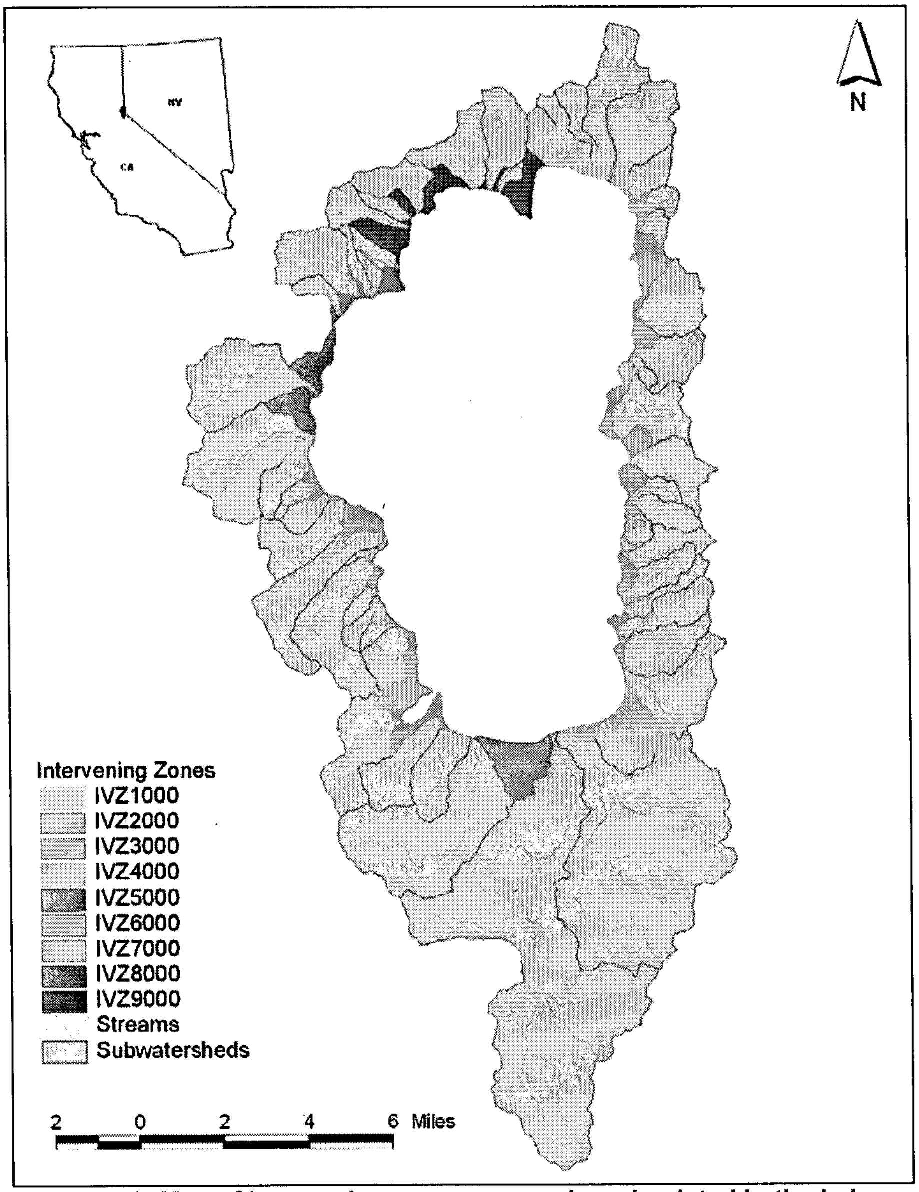

Figure 4-10. Map of intervening zones grouped as simulated in the Lake Tahoe Watershed Model (Tetra Tech unpublished).

Stream Reach Representation

Each delineated subwatershed in the Lake Tahoe Watershed Model is conceptually represented; a single stream is assumed to be a completely mixed, one-dimensional segment with a constant trapezoidal cross-section. The National Hydrography Dataset (NHD) stream reach network was used to determine the representative stream length for each subwatershed. Once the representative reach was identified, slopes were calculated based on Digital Elevation Model (DEM) data and stream lengths were measured from the original NHD stream coverage. Mean depths and channel widths for a number of segments were available from field surveys conducted by the United States Department of Agriculture (USDA)–Agricultural Research Service (Simon et al. 2003). Assuming representative trapezoidal geometry for all streams, mean stream depth and channel width were estimated, using regression curves that relate upstream drainage area to stream dimensions, and were compared with stream surveys at selected locations—General Creek (a wetter west shore of the basin) and Logan House Creek (a drier east shore of the basin). The rating curves consisted of a representative depth-outflow-volume-surface area relationship. An estimated Manning's roughness coefficient of 0.02 was applied to each representative stream reach based on typical literature values (Schwab et al. 1993).

Weather Stations and Data

Hydrologic processes are time-varying and depend on changes in environmental conditions including precipitation, temperature and wind speed. As a result, meteorological data are a critical component of watershed models.

Meteorological conditions are the driving force for nonpoint source transport processes in watershed modeling. Generally, the finer the spatial and temporal resolution available for meteorology, the more representative the modeled watershed hydrology will be. Precipitation and evapotranspiration are required as input for most watershed models. For the Lake Tahoe basin, where the snowfall/snowmelt process is the most significant factor in basin-wide hydrology, additional data (temperature, dew point temperature, wind speed and solar radiation) were required for snow simulation. This section discusses both local observed weather data used for model calibration and observed data customization to account for local influences.

Local Weather Data

An hourly time step for weather data was required to properly reflect diurnal temperature changes. For snow simulation, the model uses temperature to decide whether precipitation should be considered as rainfall or snowfall. Proper prediction of this trigger is required to ensure proper timing of water delivery to the rest of the hydrologic cycle. The timing of rainfall and snowmelt events directly relates to the timing of predicted sediment and nutrient loading. Likewise, the Lake Clarity Model requires proper timing of watershed boundary conditions for predictive accuracy.

There were two primary data sources for locally observed weather data. One source was a series of nine SNOwpack TELemetry (SNOTEL) gages in and around the Lake Tahoe basin maintained by USDA's Natural Resources Conservation Service (NRCS). The SNOTEL sites record air temperature, precipitation, and snow water equivalent data (used for snowfall/snowmelt calibration). The other data source was the National Climatic Data Center (NCDC), which maintains a network of long-term weather stations in the region. South Lake Tahoe Airport was the only hourly surface air gage inside the basin.

Table 4-11 lists the weather datasets used to generate the weather forcing files for watershed modeling and Figure 4-11 shows the location of the SNOTEL and NCDC weather stations in the watershed.

Table 4-11. Table of weather stations and associated data used to simulate weather conditions.

Station Name	Code	Agency[a]	Data Type[b]	Elevation (ft)	Available Data
Echo Peak	ECOC1	NRCS	SNOTEL	7800	Precipitation, Temperature
Fallen Leaf	FLFC1	NRCS	SNOTEL	6300	Precipitation, Temperature
Hagan's Meadow	HGNC1	NRCS	SNOTEL	8000	Precipitation, Temperature
Heavenly	HVNC1	NRCS	SNOTEL	8850	Precipitation, Temperature
Marlette	MRLN2	NRCS	SNOTEL	8000	Precipitation, Temperature
Mount Rose Ski[c]	MRSN2	NRCS	SNOTEL	8850	Precipitation, Temperature
Rubicon	RUBC1	NRCS	SNOTEL	7500	Precipitation, Temperature
Tahoe Crossing	THOC1	NRCS	SNOTEL	6750	Precipitation, Temperature
Ward Creek	WRDC1	NRCS	SNOTEL	6750	Precipitation, Temperature
South Lake Tahoe AP	93230	NCDC	Hourly	6314	Dew point, Wind, Solar Radiation
Reno AP[c]	23185	NCDC	Hourly	4410	Dew point, Wind, Solar Radiation
Emigrant Gap AP[c]	23225	NCDC	Hourly	5276	Dew point, Wind, Solar Radiation

[a]NRCS is the National Resource Conservation Service; NCDC is the National Climatic Data Center
[b]SNOTEL are SNOwpack TELemetry stations (available as daily and hourly)
[c]These weather stations are located outside the Lake Tahoe basin

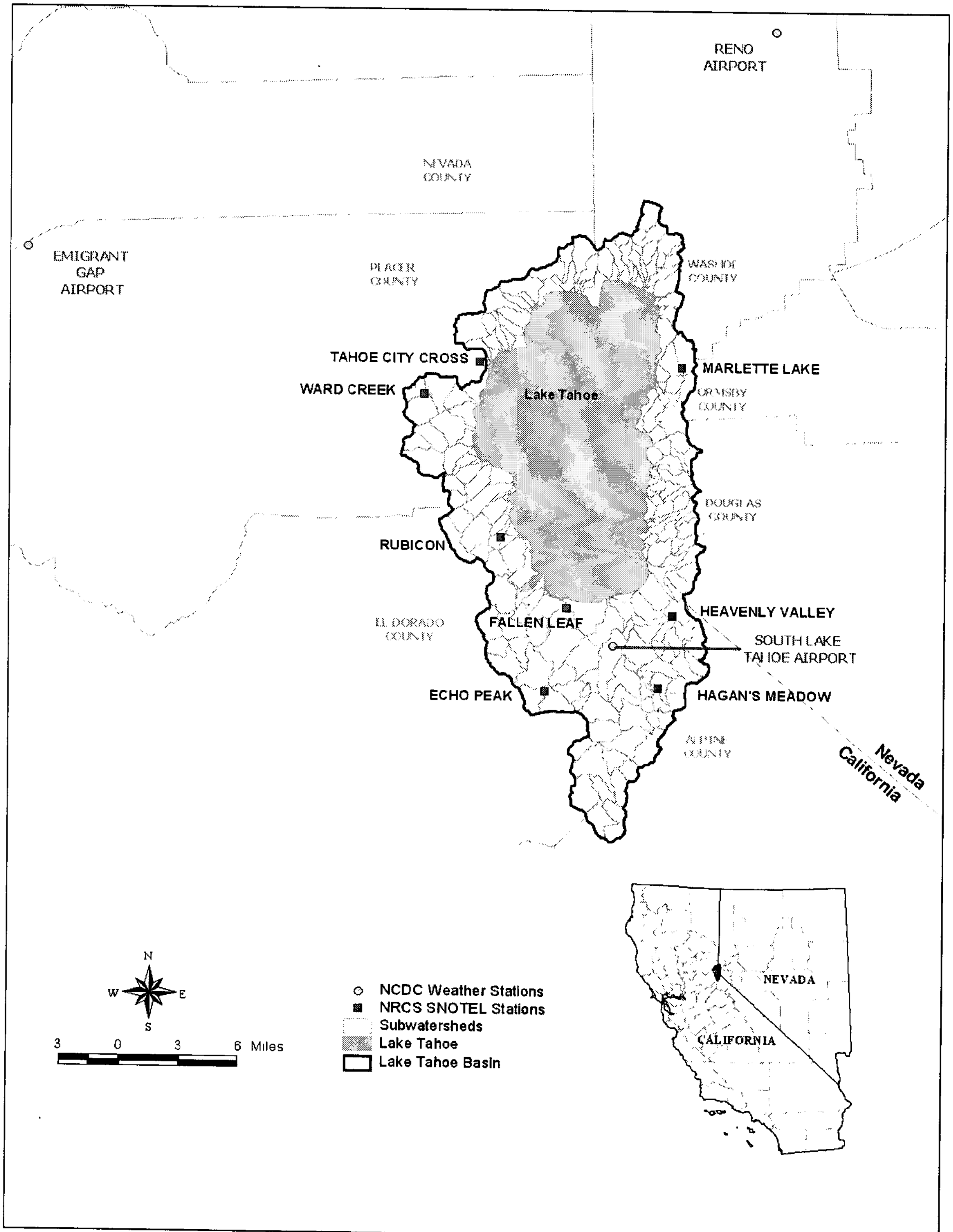

Figure 4-11. Location of SNOTEL and NCDC weather stations in the Lake Tahoe basin (Tetra Tech 2007).

Lapse Rate Calculations

A critical model parameter for snow simulation is the temperature correction for elevation changes (lapse rate). Temperature lapse rate–the rate at which temperature decreases with increasing elevation–significantly influences snowfall prediction, especially when extrapolating snow behavior to ungaged subwatersheds. This rate is particularly important in the Tahoe basin where elevation changes rapidly with distance from the lake. The Tahoe-specific lapse rate averages about 0.0022 degrees Fahrenheit (°F) per foot difference in elevation, as observed from the weather data analysis (Riverson et al. 2005, Tetra Tech 2007). The Lake Tahoe Watershed Model estimates lapse rate as a function of the elevation difference between the mean subwatershed elevation and the elevation at the location where temperature is gaged.

Evapotranspiration Calculations

Following snowfall/snowmelt simulation, evapotranspiration is arguably the second most important factor influencing Lake Tahoe basin hydrology. Evapotranspiration in the model is used to represent the sum of the evaporation and transpiration that occurs due to plants in their natural environment. The Lake Tahoe Watershed Model requires, as a weather input, the potential evapotranspiration (PEVT), which is the maximum naturally achievable amount at any given moment.

Three widely used methods to estimate evapotranspiration (ET) are the Hamon method (1961), the Jensen-Haise method (1963) and the Penman Pan-Evaporation method (1948). The Penman method, which is the earliest of these three methods, computes evaporation as a function of temperature, solar radiation, dewpoint or relative humidity, and wind movement. The other two methods, Hamon and Jensen-Haise, are simplified empirical representations that require fewer observed datasets to compute. The Hamon method is only a function of temperature, while the Jensen-Haise method requires solar radiation and temperature. The Penman method (1948) was deemed most suitable for Lake Tahoe (Riverson et al. 2005). An average vegetation (crop) factor of 0.875 (based on calibration to observed Tahoe City reference ET) was used to translate Penman pan-evaporation to PEVT.

Riverson et al. (2005) found that The annual observed evapotranspiration at Tahoe City was between 35.5 and 42.5 inches per year for reference crop (crop factor of 1.0) and evergreen forest (crop factor of 1.2), respectively. Total modeled evapotranspiration at Ward Creek is within the expected range at 37.5 inches per year

4.3.4 Land-use Representation

The Lake Tahoe Watershed Model requires a physical basis for representing the variability in hydrology and pollutant loading throughout the basin, which are both related to land-use. Land-use typically represents the primary unit for computing water quantity and quality. Non-urban and/or urban land-use areas in individual subwatersheds contribute runoff containing pollutant loads to a stream that flows to the lake. Lands adjacent to the lake route flow and pollutants directly to the lake.

Developing the Lake Tahoe land-use layer required a major effort relying on significant input from several local experts and agencies responsible for land management around the basin. A TMDL Development Team (D-Team) was formed and included key staff from the Water Board, NDEP, USFS, TRPA, California Tahoe Conservancy (CTC), the TMDL Science Coordinator and Tetra Tech. The D-team located and compiled the most current and representative GIS land-use coverage layers available, identified advantages and limitations inherent with each data source, and produced a composite layer that maximized the overall accuracy for representing land-use throughout the Lake Tahoe basin.

The adopted land-use layer is a composite based on the individual datasets that were known to have undergone their own quality assurance process. The additional effort to build this composite layer provided a more accurate spatial characterization of land-use than any other data source previously available. Spatial comparisions between the composite layer and an alternative UC Davis land-use layer are presented in the modeling report (Tetra Tech 2007). From a large set of GIS layers that varied in resolution and quality, a plan of action evolved through the data review process. Over the course of this development process, certain categories and layers were included or excluded on the basis of ground-truth comparisons, data duplication/exclusion, and site-specific information about the significance of the impact. For example, the initial list of land-uses was modified to exclude grazing (a practice that has almost disappeared from the basin and whose historical or legacy impacts are not significant for water quality) and to further refine the open space recreational category into turfed and non-turfed vegetated areas (e.g., golf-courses versus campgrounds). New layers were developed when it was detemined that existing data was inadequate (e.g. zones of forest fires, forest harvest, ski runs).

The final land-use layer was based on three primary sources of spatial data: (1) an updated parcel boundaries layer from a number of agencies comprising the Tahoe basin GIS User's Group, (2) a detailed one-square-meter resolution Hard Impervious Cover (HIC) layer that was developed using remote sensing techniques from IKONOS™ satellite imagery (Minor and Cablk 2004), and (3) a map of upland erosion potential developed by USDA National Sedimentation Lab (Simon et al. 2003). Tetra Tech (2007) provides greater detail on land-use layer development.

Land-use Categorization / Reclassification

The D-Team determined the land-use categories based on collective agreement from the various participating agencies. This involved areas with relatively similar response from a water quality modeling perspective and areas for which local or national pollutant runoff reference information could support model representation. The 140 original land-use types indicated by the parcel boundary codes were reclassified into the following six general land-use categories:

- Single-family residential (SFR)
- Multi-family residential (MFR)
- Commercial/Institutional/Communications/Utilities (CICU)
- Transportation

- Vegetated
- Waterbody

The general category of transportation includes separate subcategories for primary roads, secondary roads and unpaved roads. Primary roads were defined as the major highways that ring the lake shore with secondary roads as those city and county roads that feed into the highways. The D-Team further recognized that vegetated (non-urbanized) areas deserved special attention because they constitute over 80 percent of the basin area. Furthermore, the general vegetated lands category included a number of different land-uses (e.g., ski resorts and other recreational areas), management activities (e.g., harvesting to control overgrowth and fire hazard), and/or natural conditions (e.g., naturally burned forests) that have differing hydrologic and sediment and nutrient loading characteristics. As a result, six subcategories of vegetated land-use were defined:

1. *Unimpacted*: Forested areas that have been minimally affected in the recent past.
2. *Turf*: Land-use types with large turf areas and little impervious coverage, such as golf courses, large playing fields, and cemeteries, with potentially similar land management activities.
3. *Recreational*: Lands that are primarily vegetated and are characterized by relatively low-intensity uses and small amounts of impervious coverage. These include the unpaved portions of campgrounds, visitor centers, and day use areas.
4. *Ski Areas*: Lands within otherwise vegetated areas for which some trees have been cleared to create a run.
5. *Burned*: Areas that have been subject to controlled burns and/or wildfires in the recent past.
6. *Harvested*: Lands that management agencies have thinned in the recent past for the purpose of forest health and defensible space (areas cleared to reduce the spread of wildfire).

GIS Layering Process

To produce the land-use grid that forms the framework for the Lake Tahoe Watershed Model, a layering and intersecting process for the various land-use GIS data sources in the Tahoe basin was performed. The objective of this effort was to develop one composite grid layer that maximized the overall accuracy in representing land-use areas in the Lake Tahoe basin. Table 4-12 shows the modeling land-use categories derived from the composite land-use layer. Impervious, hard surfaces, significantly affects the capacity of surface runoff to be infiltrated, Figure 4-12 illustrates an example area with a large percentage of impervious area in the South Shore of Lake Tahoe. The impervious cover was developed by DRI using spectral mapping and transformation techniques on IKONOS™ satellite images from 2002 (Minor and Cablk 2004). The impervious cover is a one-meter resolution grid map of all anthropogenic impervious surfaces throughout the basin including rooftops and paved roads in both urbanized and rural or vegetated areas.

Table 4-12. Modeling land-use categories derived from the composite land-use layer.

Land-use Description	Pervious/Impervious	Subcategory Name
Waterbody	Impervious	Water_Body
Single Family Residential	Pervious	Residential_SFP
	Impervious	Residential_SFI
Multi Family Residential	Pervious	Residential_MFP
	Impervious	Residential_MFI
Commercial/Institutional/ Communications/Utilities	Pervious	CICU-Pervious
	Impervious	CICU-Impervious
Transportation	Impervious	Roads_Primary
	Impervious	Roads_Secondary
	Impervious	Roads_Unpaved
Vegetated	Pervious	Ski_Areas-Pervious
	Pervious	Veg_Unimpacted *
	Pervious	Veg_Recreational
	Pervious	Veg_Burned
	Pervious	Veg_Harvest
	Pervious	Veg_Turf

** This subcategory was further refined into five new subcategories based on erosion potential as defined by Simon et al. (2003).*

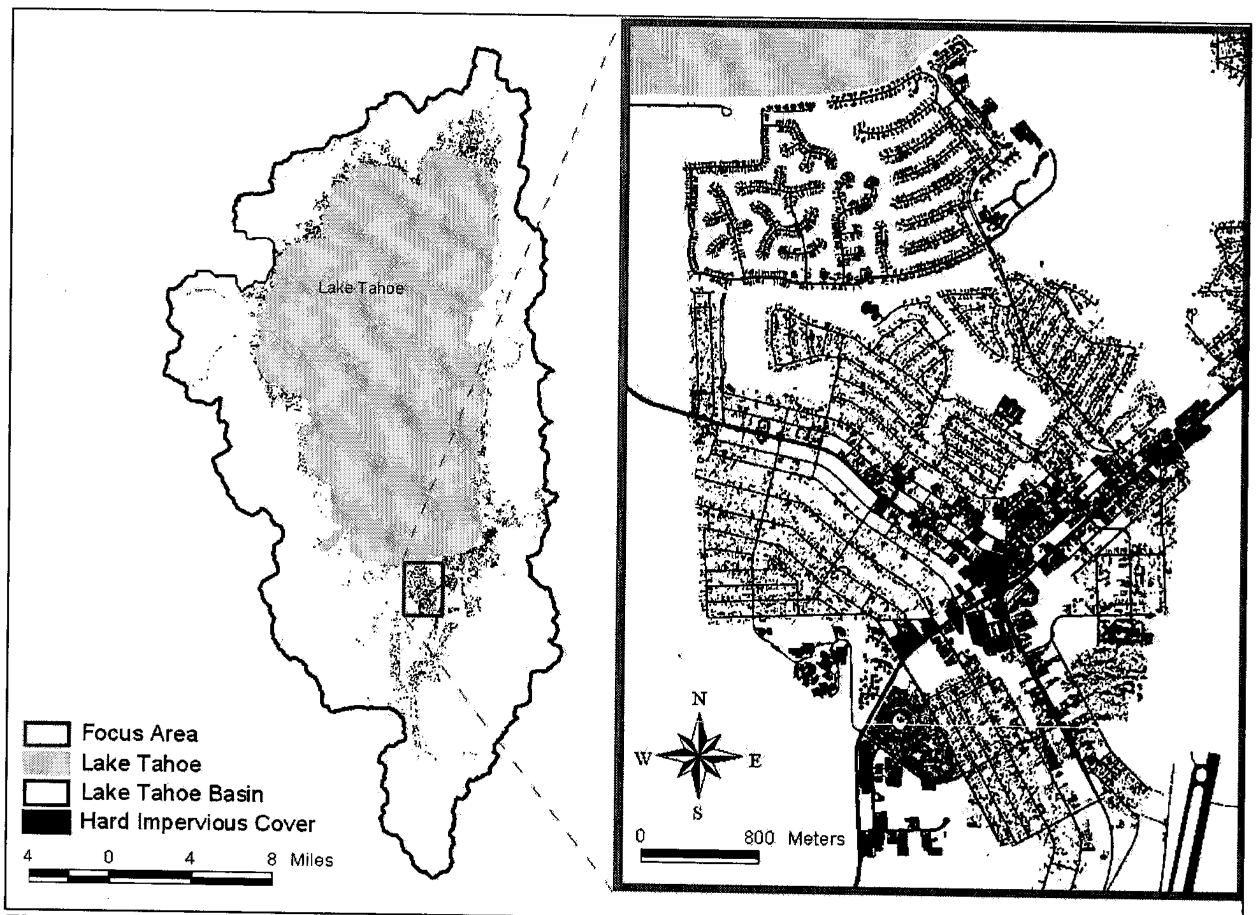

Figure 4-12. Hard impervious cover for the Lake Tahoe basin, an example focus area (Tetra Tech 2007).

Incorporating Erosion Potential for Vegetated Areas

During model development, it became evident that the land-use category classified as vegetated-unimpacted was too broad, and did not reflect significant differences in the erodibility of the soils. Further definition of this category became necessary for successful model calibration. Using the GIS coverage of upland-erosion potential for the Lake Tahoe basin developed by Simon et al. (2003), the land area initially categorized as the vegetated-unimpacted land-use was further subdivided into five erosion potential categories.

The map of upland-erosion potential for the Lake Tahoe basin (Figure 4-13) was developed independently of the TMDL land-use layer using an upland-erosion potential index based on the following parameters (Simon et al. 2003):

- Soil erodibility factor (k factor)
- Land-use
- Paved and unpaved roads, trails and streams
- Surficial geology
- Slope steepness

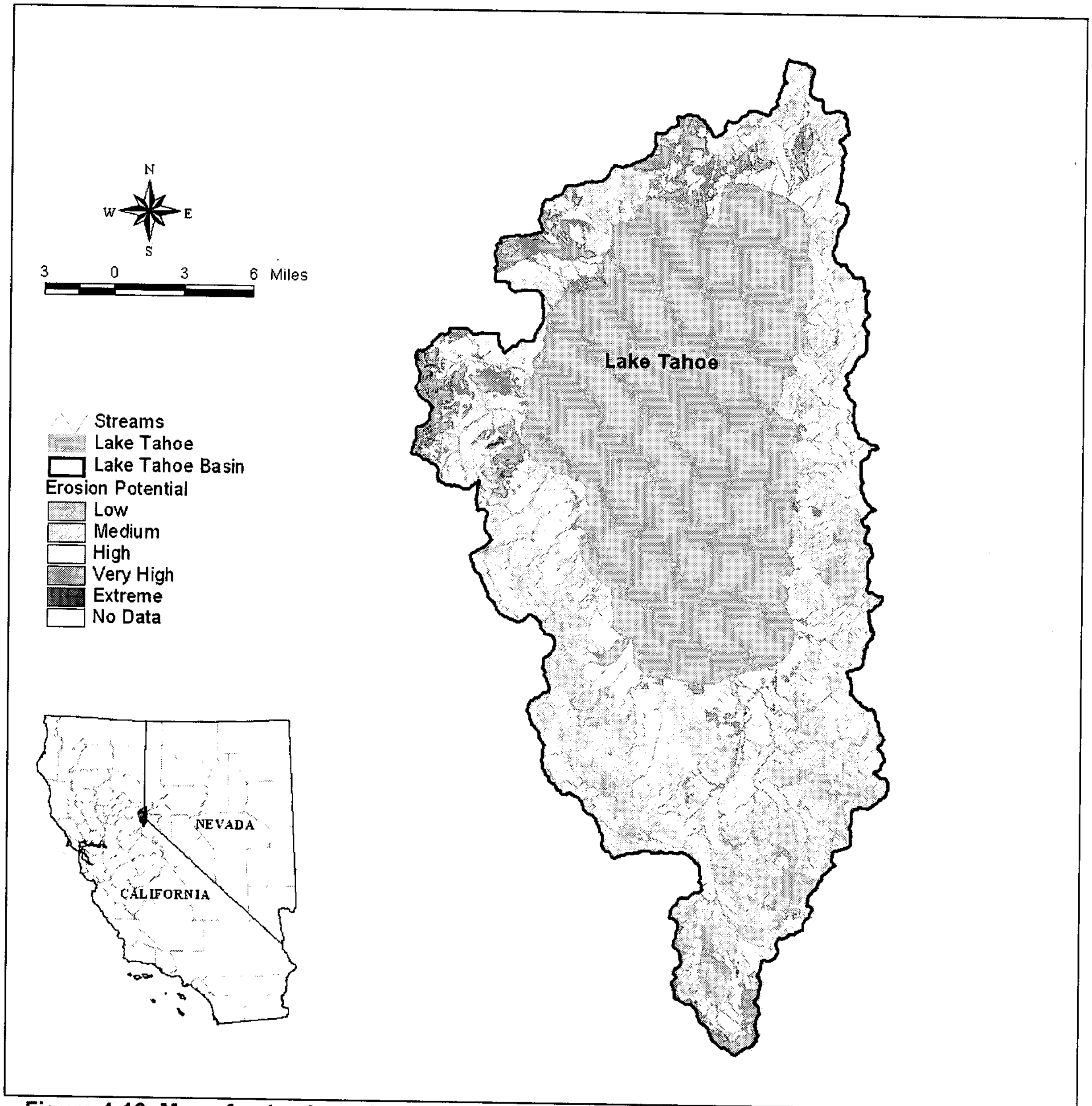

Figure 4-13. Map of upland erosion potential for the Lake Tahoe basin (Tetra Tech 2007).

The erosion potential ability of the soil was scaled numerically from 1 to 5, with the higher values indicating greater erosion potential of the soil. The map of upland erosion potential was used to subdivide the land within the broad vegetated-unimpacted category into 5 vegetated land-use categories. Table 4-13 shows the resulting breakdown of coverage in the Tahoe basin for the 5 categories. Figure 4-14 shows the land-use distribution map before the subdivision of the vegetated unimpacted areas into representative erosion potential categories, while Figure 4-15 shows the land-use distribution map after the sub-division.

Table 4-13. Percent cover of the five vegetation erosion categories (Tetra Tech 2007).

Vegetated Land-use	Percent Cover (%)
Veg_EP1	5.72
Veg_EP2	46.28
Veg_EP3	26.14
Veg_EP4	8.88
Veg_EP5	0.22
Total	**87.02**

Finally, Table 4-14 presents the final land-use distribution for the Lake Tahoe basin.

Table 4-14. Final land-use distribution for the Lake Tahoe basin (Tetra Tech 2007).

Land-use	Percent of Watershed Area (%)	Land-use	Percent of Watershed Area (%)
Veg_EP2	46.28%	Veg_Turf	0.55%
Veg_EP3	26.14%	Ski_Runs	0.54%
Veg_EP4	8.88%	CICU-Impervious	0.48%
Veg_EP1	5.72%	Residential_MFI	0.38%
Residential_SFP	4.00%	Roads_Primary	0.28%
Water_Body	1.70%	Veg_EP5	0.22%
Roads_Secondary	1.34%	Veg_Burned	0.20%
Residential_MFP	1.00%	Veg_Harvest	0.20%
Residential_SFI	0.89%	Veg_Recreational	0.17%
CICU-Pervious	0.86%	Roads_Unpaved	0.15%

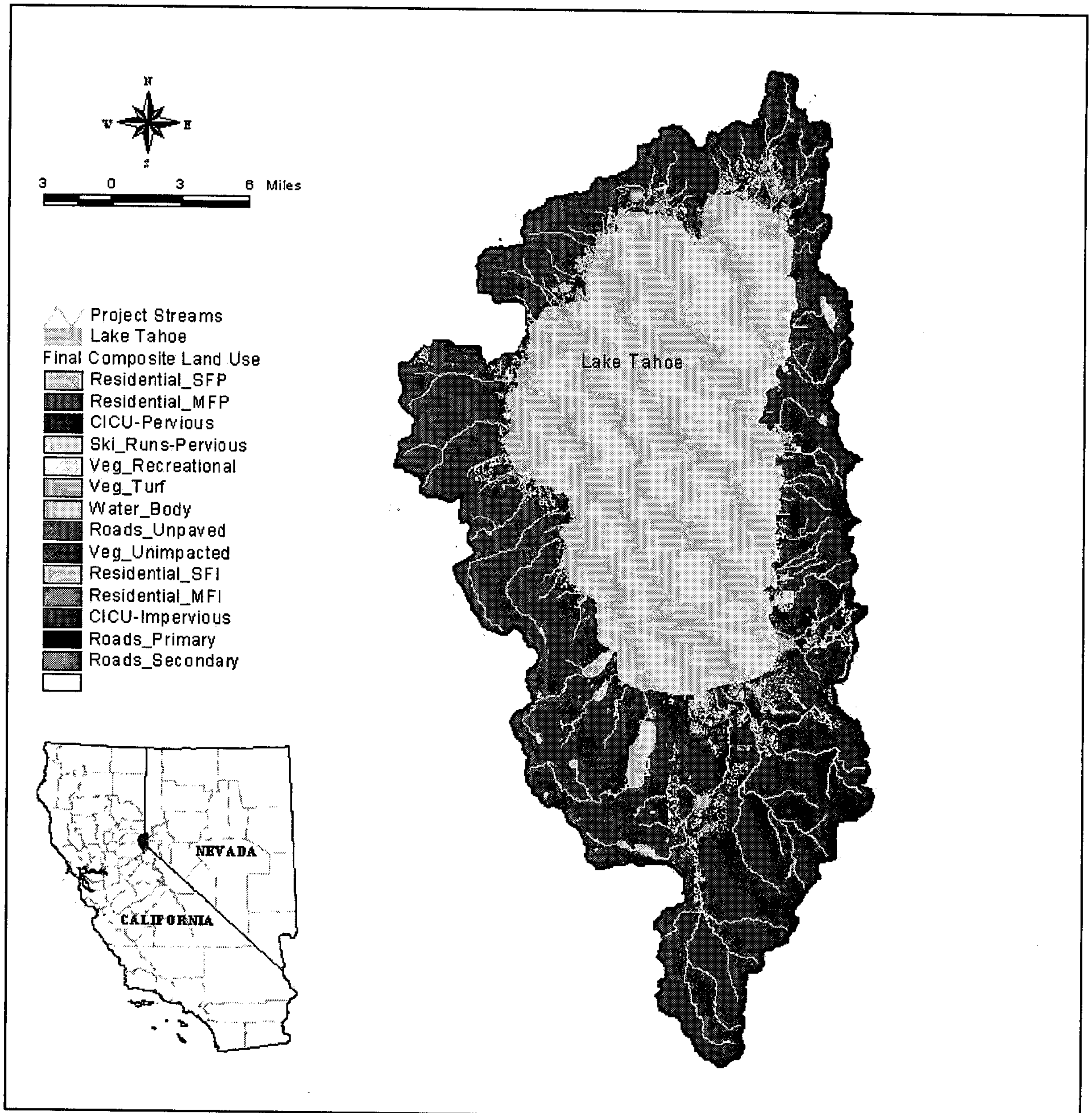

Figure 4-14. Map of land-use coverage with one classification for Vegetated Unimpacted (Tetra Tech unpublished).

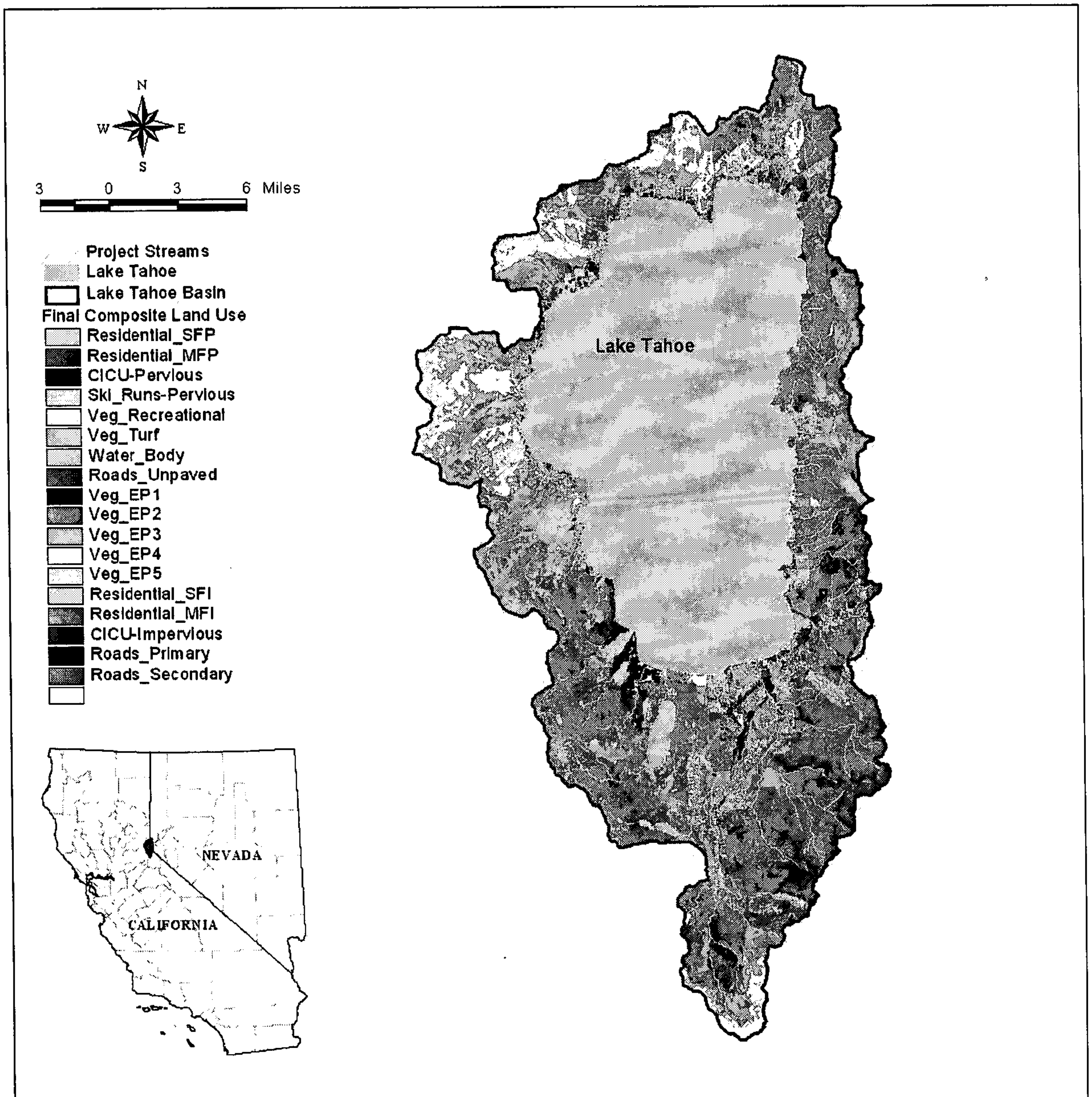

Figure 4-15. Map of land-use coverage after sub-dividing the Vegetated Unimpacted into 5 Erosion categories (Tetra Tech 2007).

4.3.5 Model Calibration

Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations based on field monitoring data. The goal of the calibration was to obtain physically realistic model prediction by selecting parameter values that reflect the unique characteristics of the watersheds around the lake. Spatial and temporal aspects were also evaluated through the calibration process.

Calibration was an iterative procedure that involved comparing simulated and observed values of interest. Calibration of the Lake Tahoe Watershed Model for the basin followed a sequential, hierarchical process that began with hydrology, followed by calibration of water quality.

Hydrology

Because inaccuracies in the hydrology simulation propagate forward into the water quality simulation, the accuracy of the hydrologic simulation has a significant effect on the accuracy of the water quality simulation. Hydrologic calibration was performed after configuring the Lake Tahoe Watershed Model and was based on several years of simulation to be able to capture a variety of climatic conditions. The calibration procedure resulted in parameter values that produce the best overall agreement between simulated and observed streamflow values throughout the calibration period. Calibration included a time series comparison of daily, monthly, seasonal and annual values, and individual storm events. Composite comparisons (e.g., average monthly streamflow values over the period of record) were also made. The Lake Tahoe Watershed Model was calibrated using both historical LTIMP stream-monitoring data and locally observed stormwater runoff monitoring data (Heyvaert et al. 2007).

The general Lake Tahoe Watershed Model hydrology algorithm follows a strict conservation of mass, with various compartments available to represent different aspects of the hydrologic cycle. Sources of water are direct rainfall or snowmelt. Potential sinks from a land segment are total evapotranspiration, flow to deep groundwater aquifers and outflow to a reach. Flow from land is routed through a network of reaches. From the individual-reach perspective, sources include land outflow (runoff and baseflow), direct precipitation and flow routed from upstream reaches. Sinks include surface evaporation, mechanical withdrawals, and reach outflow.

Ten United States Geological Survey (USGS) stream flow gages and 11 LTIMP water quality gages around the perimeter of Lake Tahoe were used for model calibration (Figure 4-16). Calibration graphs for Ward Creek are included as examples (Figure 4-18).

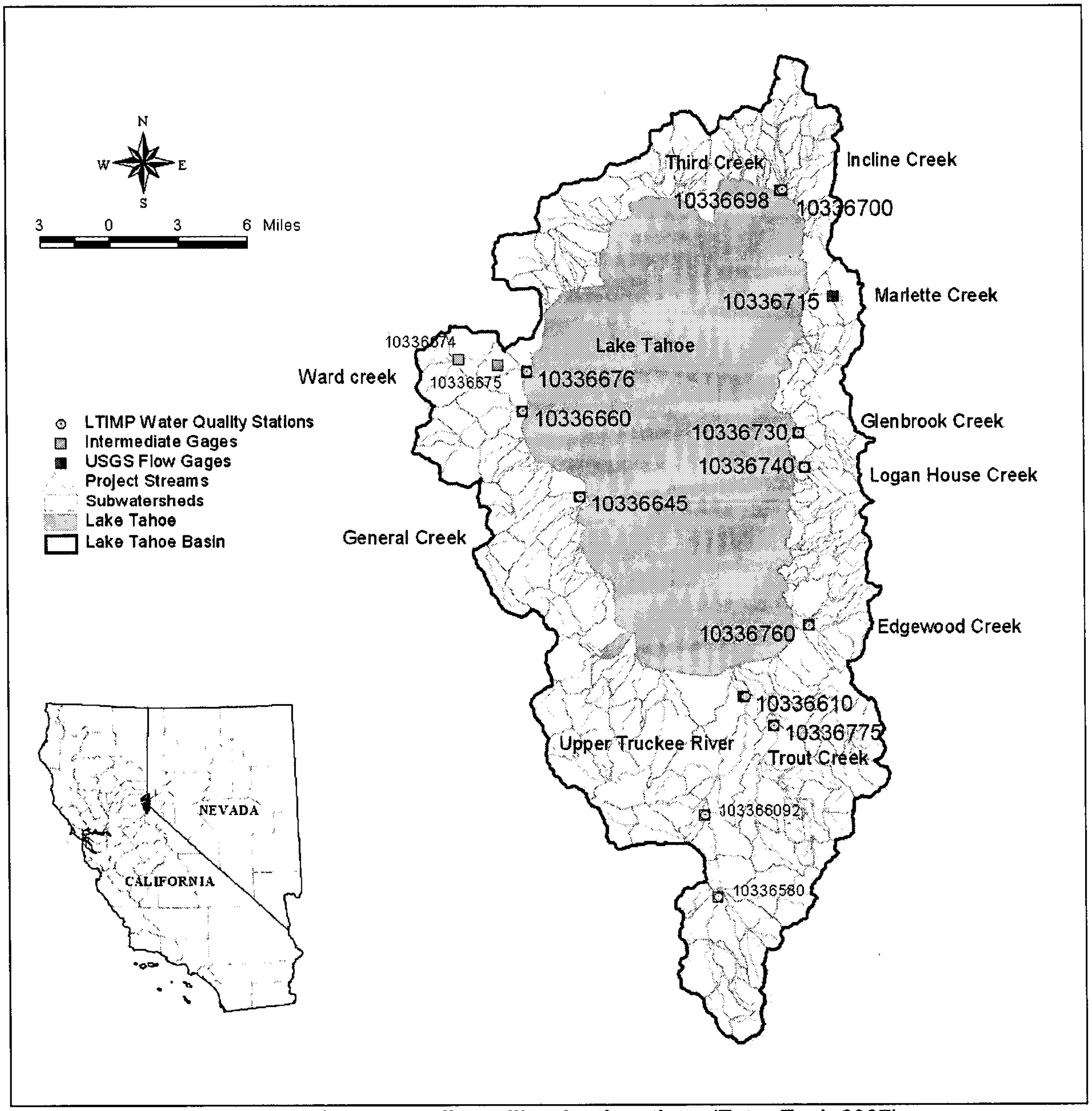

Figure 4-16. Hydrology and water quality calibration locations (Tetra Tech 2007).

Snow Processes

Snowfall and snowmelt have a dominant impact on hydrology, water quality, and management practice requirements in the Lake Tahoe basin. Therefore, calibrating snow hydrology was critical to the accuracy of the overall hydrology calibration for the basin.

An energy balance approach was used to simulate snow behavior. The Lake Tahoe Watershed Model SNOW module uses the meteorological information to determine whether precipitation falls as rain or snow, how long the snowpack remains, and when snowpack melting occurs. Heat is transferred into or out of the snowpack through net radiation heat, convection of sensible heat from the air, latent heat transfer by moist air condensation on the snowpack, from rain, and through conduction from the ground beneath the snowpack. Figure 4-17 provides the snow simulation schematic. The snowpack essentially acts like a reservoir that has specific thermodynamic rules for how water is released. Melting occurs when the liquid portion of the snowpack exceeds the snowpack's holding capacity; melted snow is added to the hydrologic cycle.

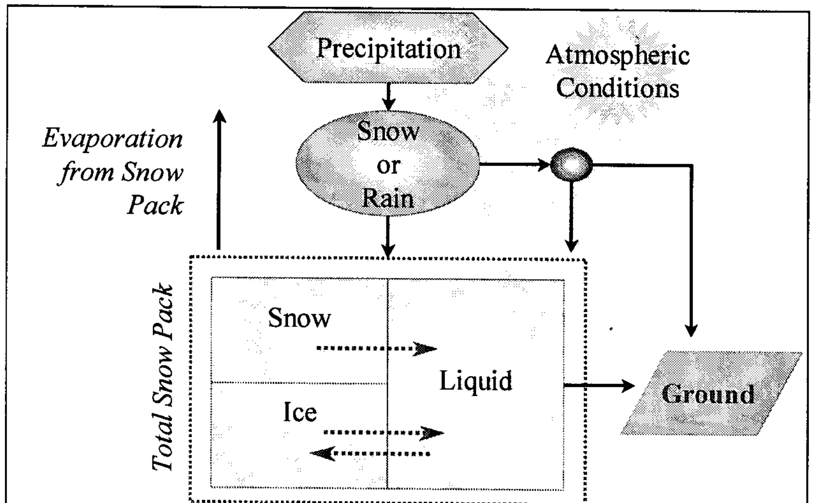

Figure 4-17. Snow simulation schematic used in the Lake Tahoe Watershed Model (Tetra Tech 2007).

Daily average snow water equivalent (SWE) data at the SNOTEL sites were directly compared with modeled SWE output. Emphasis was given to overall volumes and the shape of the SWE curve. Figure 4-18 shows an example of modeled versus observed daily average temperatures and SWE depths at Ward Creek. The upper graph shows temperature (right axis), volume (left axis), and precipitation type. When the temperature falls below the solid brown line, precipitation becomes snowfall; rainfall volumes are the dark blue bars, and snowfall volumes are the light blue bars. The lower graph, which shows modeled SWE in gray and observed SWE as blue dots, demonstrates consistently good agreement year after year through eight annual snowfall/snowmelt cycles.

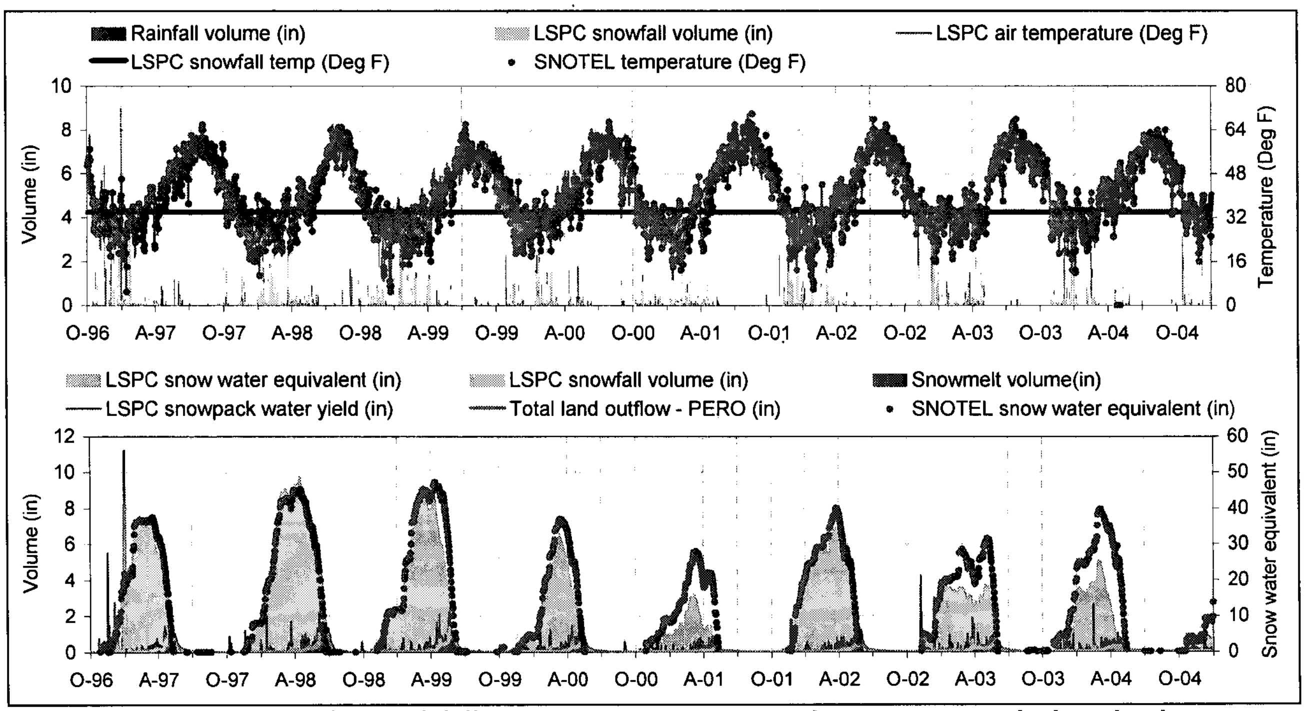

Figure 4-18. Modeled vs. observed daily average temperatures and snow water equivalent depths at Ward Creek SNOTEL site from October 1996-December 2004, note LSPC is the Lake Tahoe Watershed Model output (Tetra Tech 2007).

During model testing and calibration, it became evident that the most important factor influencing the model snow predictions was not the calibration parameters, but the quality of the input temperature time series. The SNOTEL quality assurance process for temperature, together with the lapse rate correction, noticeably reduced overall model error. The calculation of the lapse rate (the rate at which temperature decreases with increasing elevation) in the Lake Tahoe basin was critical to the accuracy of the Lake Tahoe Watershed Model because it influences snowfall prediction, which significantly affects the hydrology of the basin.

Discharge

During calibration, agreement between observed and simulated stream flow data was evaluated on an annual, seasonal, and daily basis using quantitative and qualitative measures. Specifically, annual water balance, groundwater volumes and recession rates, and surface runoff and interflow volumes and timing were evaluated. The hydrologic model was calibrated by first adjusting model parameters until the simulated and observed annual and seasonal water budgets matched. Then the intensity and arrival time of individual events were calibrated. This iterative process was repeated until the simulated results closely represented the system and reproduced observed flow patterns and magnitudes. The model calibration was performed using the guidance of error statistics criteria specified in HSPEXP (Lumb et al. 1994). Output comparisons included mean runoff volume for simulation period, monthly runoff volumes, daily flow time series, and flow frequency curves.

Lake Tahoe Watershed Model hydrology algorithms follow a strict conservation of mass. The sources of water to the land surface are either direct precipitation or snowmelt. Some of this water is intercepted by vegetation, man-made structures, or by other means. The interception is represented in the model like a land-use-specific "reservoir" that must be filled before any excess water is allowed to overflow to the land surface. The water in the "reservoir "is also subject to evaporation. The size, in terms of inches per unit of area, of this reservoir can be varied monthly to represent the level of each compartment (both above and below the land surface).

Water that is not intercepted is placed in surface detention storage. If the land segment is impervious, no subsurface processes are modeled, and the only pathway to the stream reach is through direct surface runoff. If the land segment is pervious, the water in the surface detention storage can infiltrate, be categorized as potential direct runoff or be divided between runoff and infiltration. This decision is made during simulation as a function of soil moisture and infiltration rate. The water that is categorized as potential direct runoff is partitioned into surface storage/runoff, interflow, or kept in the upper zone storage. Surface runoff that flows out of the land segment depends on the land slope and roughness, and the distance it has to travel to a stream. Interflow outflow recedes based on a user-defined parameter.

Water that does not become runoff, interflow, or lost to evaporation from the upper zone storage will infiltrate. This water will become part of the lower zone storage, active groundwater storage or be lost to the deep/inactive groundwater. The lower zone storage acts like a reservoir of the subsurface. Within the Lake Tahoe Watershed Model, this reservoir needs to be full in order for water to reach the groundwater storage. Groundwater is stored and released based on the specified groundwater recession, which can be made to vary non-linearly.

The model attempts to meet the evapotranspiration demand by evaporation of water from baseflow (groundwater seepage into the stream channel), interception storage, upper zone storage, active groundwater, and lower zone storage. How much of the evapotranspiration demand is allowed to be met from the lower zone storage is determined by a monthly variable parameter. Finally, within the Lake Tahoe Watershed Model water can exit the system in three ways: evapotranspiration, deep/inactive groundwater, or entering the stream channel. The water that enters the stream channel can come from direct overland runoff, interflow outflow, and groundwater outflow.

Some of the hydrologic parameters can be estimated from measured properties of the watersheds while others must be estimated by calibration. Model parameters adjusted during calibration are associated with evapotranspiration, infiltration, upper and lower zone storages, recession rates of baseflow and interflow, and losses to the deep groundwater system.

During hydrology calibration, land segment hydrology parameters were adjusted to achieve agreement between daily average simulated and observed USGS stream flow at selected locations throughout the basin, as previously shown in Figure 4-16. The average of the 24 hourly model predictions per day was compared to daily mean flow values measured at USGS streamflow gauges throughout the basin. The four-year calibration period was from 10/01/1996 to 9/30/2000. Although the model was run from January 1996 through December 2004, the first 9 months are disregarded to allow for model predictions to stabilize from the effects of estimated initial conditions.

Insights gained from calibration are that about 70 percent of the total annual water budget arrives during spring snowmelt and that as a basin-wide average, baseflow (which includes water that infiltrates into the subsurface regime from the surface) accounts for more than 90 percent of the annual stream water budget. This distribution changes in the more urbanized intervening zones, where runoff percentage is proportional to the impervious area. Most of the groundwater is from snowmelt, which has the ability to infiltrate rather than immediately enter the stream channel as surface runoff because the snowmelt process occurs relatively slowly. The timing of the hydrograph was directly related to the modeling of the snow component. It became clear that the level of detail achieved in the snow calibration was necessary for a good calibration of stream flows.

Groundwater recession rates had spatial and seasonal variability. The rates were found to be nonlinear, with a steeper curve during the spring that tapered off during summer and fall. The use of a model parameter that allows for nonlinear recession rates was necessary to represent this variability in the recession rates.

Figure 4-19 shows example results over the model calibration period at Ward Creek, with emphasis on water year 1997. Figure 4-19 also shows that the model is robust enough to predict an extreme 100-year rain-on-snow event (January 1, 1997) while also capturing low-flow variability, as seen by exaggerating low flows using a log-scale. Validation was performed for a longer time period (10/1/1996 through 12/31/2004). Figure 4-20 shows model results for the full validation period at Ward Creek. Results are month-aggregated to evaluate the model's ability to reproduce consistent seasonal trends. Model performance statistics are shown in Table 4-15.

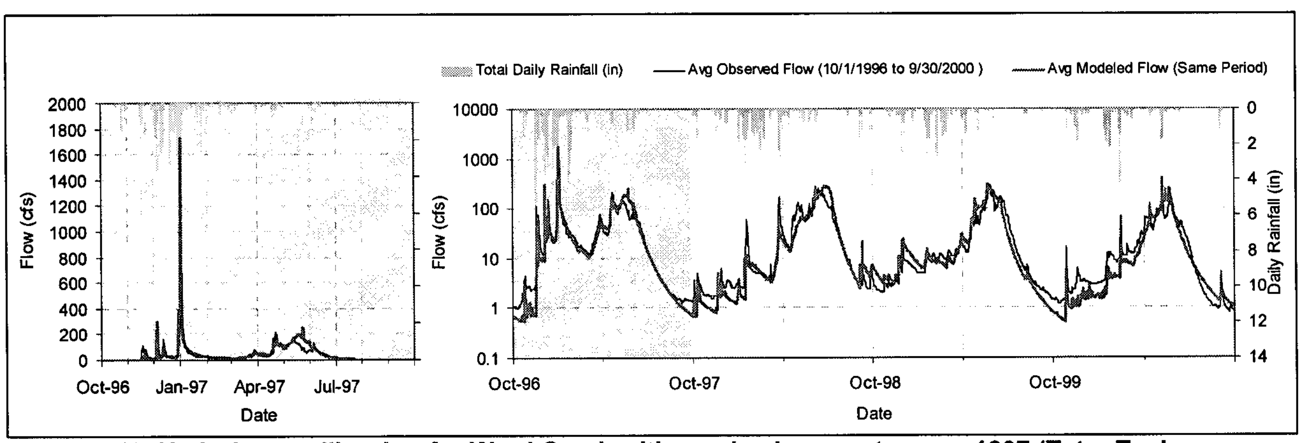

Figure 4-19. Hydrology calibration for Ward Creek with emphasis on water year 1997 (Tetra Tech 2007).

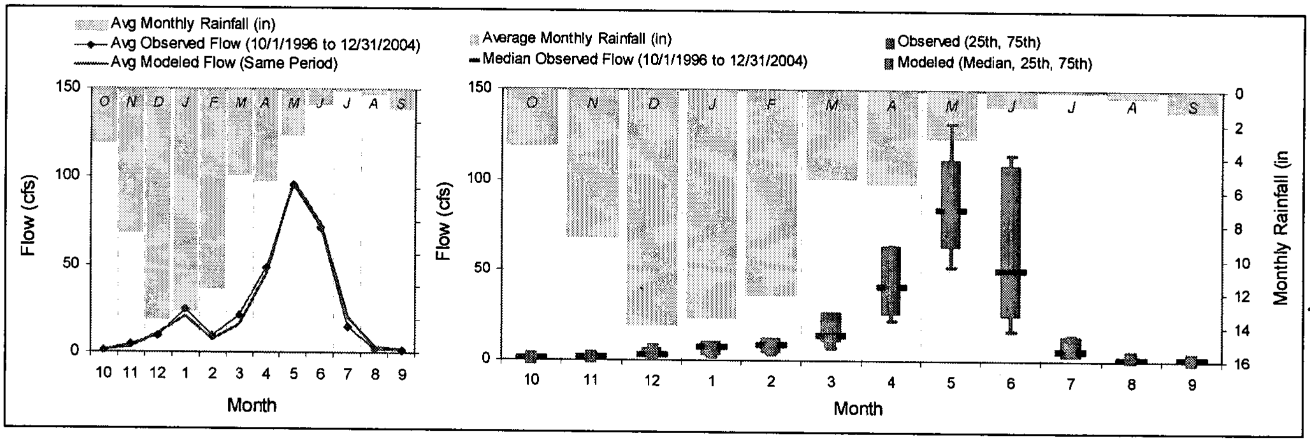

Figure 4-20. Hydrology validation for Ward Creek with seasonal mean, median and variation (Tetra Tech 2007).

Table 4-15. Hydrology validation summary statistics for Ward Creek (note: LSPC is the Lake Tahoe Watershed Model) (Tetra Tech 2007).

LSPC Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM SUBBASIN 8060 8.25-Year Analysis Period: 10/1/1996 - 12/31/2004 Flow volumes are normalized, with total observed as 100		**USGS 10336676 WARD C AT HWY 89 NR TAHOE PINES CA** Placer County, California Hydrologic Unit Code 16050101 Latitude 39°07'56", Longitude 120°09'24" NAD27 Drainage area 9.70 square miles	
Total Simulated In-stream Flow:	**99.19**	Total Observed In-stream Flow:	**100.00**
Total of simulated highest 10% flows:	**58.50**	Total of Observed highest 10% flows:	**53.93**
Total of Simulated lowest 50% flows:	**4.54**	Total of Observed Lowest 50% flows:	**4.21**
Simulated Summer Flow Volume (months 7-9):	**8.49**	Observed Summer Flow Volume (7-9):	**6.02**
Simulated Fall Flow Volume (months 10-12):	**5.70**	Observed Fall Flow Volume (10-12):	**5.59**
Simulated Winter Flow Volume (months 1-3):	**14.46**	Observed Winter Flow Volume (1-3):	**18.24**
Simulated Spring Flow Volume (months 4-6):	**70.54**	Observed Spring Flow Volume (4-6):	**70.15**
Total Simulated Storm Volume:	**7.03**	Total Observed Storm Volume:	**8.29**
Simulated Summer Storm Volume (7-9):	**0.54**	Observed Summer Storm Volume (7-9):	**0.40**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-0.81	10		
Error in 50% lowest flows:	7.32	10		
Error in 10% highest flows:	7.80	15		
Seasonal volume error - Summer:	29.12	30		
Seasonal volume error - Fall:	2.01	30		
Seasonal volume error - Winter:	-26.12	30		
Seasonal volume error - Spring:	0.55	30		
Error in storm volumes:	-18.06	20		
Error in summer storm volumes:	26.03	50		

In general, the model produced excellent snow and hydrology results when model inputs were spatially derived from site-specific data and when weather data quality were validated. Performance statistics show that the model reproduced observed trends very well. Table 4-16 shows the validation summary statistics for the other flow gages in the Lake Tahoe basin.

Table 4-16. Hydrology validation summary statistics for USGS flow gages in the Lake Tahoe basin (Tetra Tech 2007).

Watershed	USGS Station ID	Location	Drainage Area (sq-mi)	% Error in Total Volume	% Error in 50% Lowest Flows	% Error in 10% Highest Flows
Upper Truckee	10336610	Upper Truckee River at South Lake Tahoe, CA	54.9	4.1	-14.6	5.0
Upper Truckee	103366092	Upper Truckee River at Hwy 50 above Meyers, CA	34.3	9.1	-26.0	9.7
Upper Truckee	10336580	Upper Truckee River at South Upper Truckee Rd nr Meyers, CA	14.1	0.8	2.6	-13.0
Blackwood	10336660	Blackwood Creek near Tahoe City, CA	11.2	-6.2	-8.7	7.4
Ward	10336676	Ward Creek at Hwy 89 near Tahoe Pines, CA	9.7	-0.8	7.4	7.8
General	10336645	General Creek near Meeks Bay, CA	7.4	-4.3	-7.3	1.0
Incline	10336700	Incline Creek near Crystal Bay, NV	6.7	1.7	-2.6	8.8
Edgewood	10336760	Edgewood Creek at Stateline, NV	5.6	2.1	0.7	21.8
Glenbrook	10336730	Glenbrook Creek at Glenbrook, NV	4.1	7.8	-0.6	3.4
Logan House	10336740	Logan House Creek near Glenbrook, NV	2.1	10.7	30.1	6.1

As a final validation, the annual hydrologic budget estimates from streamflow into Lake Tahoe were compared to previously published estimates. Table 4-17 shows the results of this comparison. The Lake Tahoe Watershed Modeled stream flows fall right in between the other estimates.

Table 4-17. Hydrologic Budget Estimates for Lake Tahoe (Stream-flow Component) (Tetra Tech 2007).

Reference	Period Considered	Estimate Annual Streamflow into Lake Tahoe (acre-ft)
McGauhey and others, 1963	1901-62	308,000
Crippen and Pavelka, 1970	1901-66	312,000
Dugan and McGauhey, 1974	1960-69	372,000
Myrup et al. 1979	1967-70	413,000
Marjanovic, 1987		379,562
Lake Tahoe Watershed Model (LSPC) Tetra Tech 2007	**1990-2002**	**376,211**

Water Quality

The water quality component of the Lake Tahoe Watershed Model is dependent on the modeled hydrology. Sediment production is directly related to the intensity of surface runoff and its yield varies by spatially land-use throughout the basin. Besides meteorology and the resulting hydrology, sediment yield is also influenced by factors including, but not limited to, soil type, surface cover and soil erodibility. Sediment is delivered to the tributaries and to Lake Tahoe through surface runoff erosion and in-stream bank erosion.

Nutrients are delivered to the tributaries with surface runoff and subsurface flow. They may be observed in both organic and inorganic forms, and may exist in both dissolved and particulate forms. Some nutrient forms, such as phosphorus are also associated with sediment. The Lake Tahoe Watershed Model provides mechanisms for representing these various pathways of pollutant delivery.

The Lake Tahoe Watershed Model is set up to model in-stream transformations, but given the relatively fast time of concentration (i.e. the time of travel from the headwaters to mouth of the tributaries is only on the order of hours) the additional effort - and required assumptions - to represent these transformations was not considered to be significant during periods of elevated flow. While biological transformations could be of consideration during the summer period of very low baseflow when residence time is higher, loading during that period is minor.

A detailed water quality analysis was performed using statistically-based load estimates with observed flow and in-stream monitoring data. The confidence in the calibration process increases with the quantity and quality of the monitoring data. The LTIMP stream database provides very good spatial and temporal coverage that focuses primarily on nutrients and sediment. This analysis provides the necessary information to inform the model parameterization and calibration.

This section describes the statistical analysis, model parameterization and model calibration process for water quality.

Estimating Sediment Loads through Log-Transform Regression

Since a primary objective of the Lake Tahoe Watershed Model is to estimate pollutant loads for use in the lake clarity model, accurate estimates of loads based on the LTIMP monitoring data had to be developed to aid in the water quality calibration process.

Suspended sediment loads are typically estimated using linear regression of observed sediment load versus stream flow datasets. Since sediment load and stream flow are storm driven, observed values for both often span several orders of magnitude. For this reason, the in-stream sediment load versus flow relationship tends to be linear when plotted on logarithmic scales. For practical application of the regression model, estimated loads must be re-transformed from the log transformations back to the original units. Since this retransformation process may be statistically biased, one of the methods that the USGS recommended for bias correction is the Minimum Variance Unbiased Estimator (MVUE) (Cohn and Gilroy 1991). The objective of this method is to yield an unbiased estimate with the smallest possible variance.

Many years of research have refined this statistical retransformation method and made it practical for estimating loads for environmental engineering applications (Finney 1941, Bradu and Mundlak 1970, and Cohn et al. 1989). In addition to sediment, the

MVUE re-transformation has also been applied in numerous studies to other pollutants that exhibit log-normal relationship including total and dissolved nitrogen and phosphorus species (e.g. MDNR and USGS 2001, Green and Haggard 2001). It is important to note that this method is only unbiased if the regression errors are normally distributed when presented as logs.

An estimate of in-stream sediment loads from upland and channel or stream sources was developed for each of the 10 calibration watersheds using this method. Table 4-18 shows the annual estimates of TSS loads for calibration streams (NOTE: values given the tables associated with this section are for the 10 LTIMP streams only and do not represent basin-wide loading estimates. The basin-wide loading estimates from the Lake Tahoe Watershed Model are given in Section 4.3.6).

Table 4-18. Annual estimates of TSS loads for calibration streams developed using the MVUE.

Watershed	TSS (metric tons)	TSS Contribution by Modeled Watershed (%)
Third Creek	819	5.3%
Incline Creek	419	2.7%
Glenbrook Creek	40	0.3%
Logan House Creek	10	0.1%
Edgewood Creek	49	0.3%
General Creek	388	2.5%
Blackwood Creek	5,127	33.0%
Ward Creek	3,166	20.4%
Trout Creek	422	2.7%
Upper Truckee River	5,091	32.8%
TOTAL	**15,531**	**100%**

Once the annual average TSS loads were determined using the MVUE, the next step was to quantify the portion of the load composed of particles finer than 63 μm in diameter. Percent of total load contributed by fines for each of the 10 calibration watersheds was obtained from *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources* (Simon 2006). The fine sediment percentage, together with the previous total load estimates, was multiplied to estimate total fine sediment by watershed (Table 4-19). As a result, the final estimate is consistent with the MVUE total load estimate while maintaining the relative distribution (in terms of percentage) as published by Simon (2006).

Table 4-19. Annual average total fine sediment outlet loads (upland and stream channel loads) estimate by calibration watershed.

Watershed	Annual Average TSS Load (metric tons/year)	Fines < 63μm[a] (%)	Annual Average Total Fines Load (metric tons/year)	Fine Sediment by Modeled Watershed (%)
Third	819	31%	254	3.7%
Incline	419	67%	281	4.1%
Glenbrook	40	80%	32	0.5%
Logan House	10	75%	7	0.1%
Edgewood	49	59%	29	0.4%
General	388	29%	113	1.6%

Watershed	Annual Average TSS Load (metric tons/year)	Fines < 63μm[a] (%)	Annual Average Total Fines Load (metric tons/year)	Fine Sediment by Modeled Watershed (%)
Blackwood	5,127	45%	2,307	33.4%
Ward	3,166	47%	1,488	21.5%
Trout	422	38%	160	2.3%
Upper Truckee	5,091	44%	2,240	32.4%
TOTAL	**15,531**	**44%**	**6,911**	**100.0%**

[a]From Simon (2006)

Because stream channel erosion is being considered discretely from the upland source category, the third step involved estimating the annual average channel fines load. Simon (2006) presents fine sediment from channel stream banks relative to total fines load at the stream outlet. This percentage was applied to the total outlet fines estimate from the previous step to estimate the channel fines contribution (Table 4-20).

Table 4-20. Annual average channel fine sediment outlet load estimate by calibration watershed.

Watershed	Annual Average Total Fines Load (metric tons/yr)	Fine Grained Contribution from Stream banks (%)	Channel Fines Load (metric tons/yr)	Percent TSS Contribution (%)
Third	253.9	10%	24.6	0.8%
Incline	280.9	4%	10.3	0.3%
Glenbrook	32.1	46%	14.8	0.5%
Logan House	7.2	1%	0.04	0.0%
Edgewood	28.9	19%	5.4	0.2%
General	112.6	45%	50.5	1.6%
Blackwood	2,307.0	51%	1,176.1	38.2%
Ward	1,487.9	25%	375.1	12.2%
Trout	160.4	2%	2.4	0.1%
Upper Truckee	2,240.1	63%	1,418.2	46.1%
TOTAL	**6,911.0**	**45%**	**3,077.4**	**100.0%**

The upland fine sediment load entering tributaries that reaches the outlet of the watershed, consequently, becomes the difference between the total fines load and the channel fines load (Table 4-21). A target value for upland fine sediment load was derived using the model's estimate of the percent of the upland fine sediment load that reaches the lake for each tributary.

Table 4-21. Annual average upland fine sediment outlet load estimate by calibration watershed.

Watershed	Annual Average Total Fines Load (metric tons/year)	Channel Fines Load (metric tons/year)	Upland Fines Loads Reaching the Lake (metric tons/year)	Percent TSS Contribution (%)
Third	253.9	24.61	229.3	6.0%
Incline	280.9	10.29	270.6	7.1%
Glenbrook	32.1	14.82	17.3	0.5%
Logan House	7.2	0.04	7.2	0.2%
Edgewood	28.9	5.42	23.5	0.6%
General	112.6	50.45	62.1	1.6%

Blackwood	2,307.0	1,176.10	1,131.0	29.5%
Ward	1,487.9	375.06	1,112.8	29.0%
Trout	160.4	2.43	158.0	4.1%
Upper Truckee	2,240.1	1,418.22	821.9	21.4%
TOTAL	**6,911.0**	**3,077.4**	**3,833.7**	**100.0%**

As shown in the tables above, a majority of the TSS loading from upland sources is from Blackwood Creek, Ward Creek and the Upper Truckee River watersheds.

<u>Pollutant Export Analysis Using Regression and Hydrograph Separation</u>

Hydrology is the driving force for the Lake Tahoe Watershed Model general water quality module (GQUAL). Since wastewater is exported out of the Tahoe basin, nonpoint sources represent the major source of pollutant loading to Lake Tahoe streams. Stream bank erosion has also been shown to represent another source of sediment loading (and associated nutrients) to Lake Tahoe. There are no known point source pollutant dischargers in the basin. The GQUAL module requires that loading rates or concentrations are specified for groundwater, interflow, and surface runoff for each land-use in each subwatershed. A statistical data 'mining' exercise was performed to 1) understand the seasonality and trends observed in both in-stream and stormwater monitoring data, 2) represent nutrient species distribution and loading patterns in baseflow versus stormflow samples, 3) estimate organic and inorganic nutrient quantities, 4) characterize particulate and sediment associated nutrient mass and 5) derive land-use specific loading rates to apply in the Lake Tahoe Watershed Model.

The primary source of in-stream monitoring is a high-resolution historical water quality dataset collected at numerous sites by the LTIMP. The constituents that have been monitored include ammonia (NH_4), total Kejdahl nitrogen (TKN), nitrate (NO_3), soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended sediment (TSS). For the purpose of this investigation, the data have been aggregated into five categories: TSS, TN, TP, dissolved inorganic-N (NO_3 + NH_4) and soluble-P. Nitrite levels, while measured, are so low that they are of no consequence to inorganic nitrogen loading in the Tahoe basin.

Hydrograph separation used in conjunction with log-transform regrèssion allows the assessment of baseflow and surface runoff volumes and associated nutrient yield. Again, baseflow is defined as flow that enters a tributary through its bottom or channel walls. Baseflow can occur at any time. During the summer when precipitation is negligible, most all of the flow in the stream channels comes from baseflow; but as shown in Figure 4-21, baseflow occurs throughout the year. The USGS hydrograph separation algorithms (HYSEP) were used to perform hydrograph separation on the observed flow time series (Sloto and Crouse 1996). Figure 4-21 presents the results of the hydrograph separation and shows that streamflow in the Lake Tahoe basin tends to be groundwater-dominant.

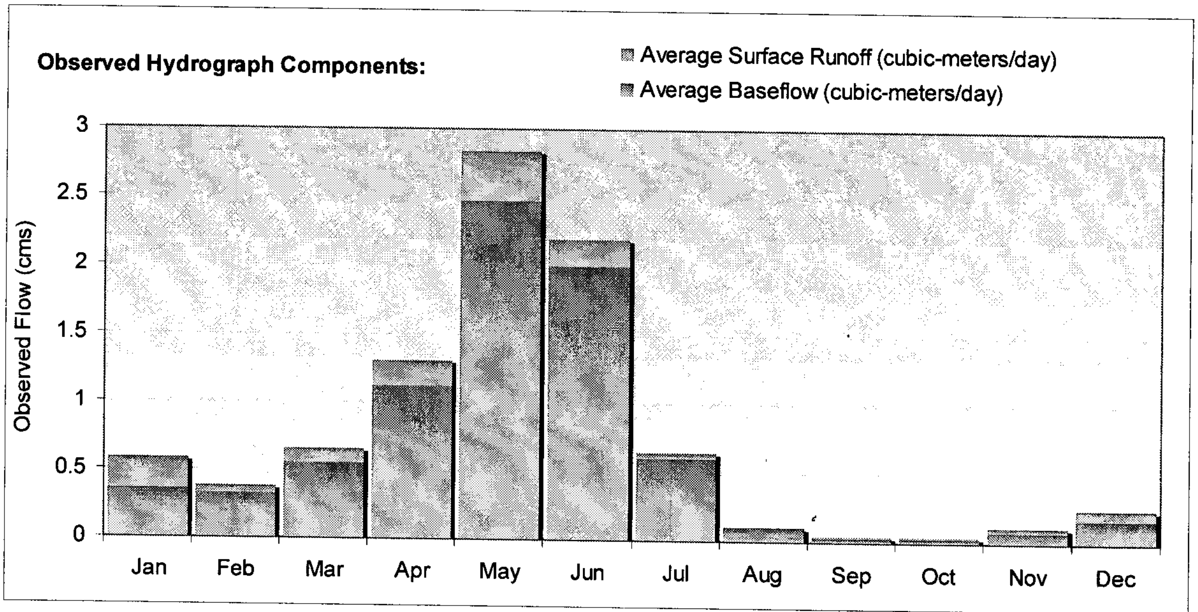

Figure 4-21. Hydrograph separation for Ward Creek (USGS 10336676) using historical flow data collected between 10/1/1972 and 9/30/2003 (Tetra Tech 2007).

Since there are no direct point source contributions of nutrients to the streams, the sediment and nutrient yields at the monitoring station are assumed to have come from upstream nonpoint sources. The following assumptions were applied for this analysis:

- Reasonable baseflow and surface runoff volumes can be obtained using the HYSEP sliding-interval method, as defined by Sloto and Crouse (1996)
- Since flow-versus-load regressions have errors that are normally distributed in log space, it is reasonable to use rating curves in conjunction with MVUEs to develop baseflow and surface runoff load relationships in linear space
- TN and TP represent all transportable nitrogen and phosphorus from upstream sources
- Baseflow pollutant load is primarily groundwater driven and storm-flow pollutant load is primarily surface runoff driven
- Baseflow associated samples are composed primarily of dissolved inorganic nutrients (dissolved nitrogen and dissolved phosphorus)
- TN and TP baseflow samples represent total dissolved nutrients, which include both organic and inorganic forms
- TSS, which is primarily associated with surface runoff, includes organic material that contains nutrients
- Baseflow rating curves can be used in conjunction with total flow rating curves to back-calculate surface runoff nutrient loading
- Surface runoff pollutant mass is composed of primarily particulate constituents
- Particulate nutrient mass is primarily composed of organic material
- Particulate-nutrient-mass to sediment-mass ratios represent sediment-associated nutrients

For each LTIMP gage, a set of ten regression rating curves were developed using the monitoring data. For each water quality constituent, a baseflow (BF) and storm-flow (RO) curve was derived using the separated hydrograph. A set of example equations are presented in Table 4-22. For the development of the rating curves, each instream sample had to be classified as either a BF sample or a RO sample using the daily separated hydrograph timeseries. It was reasonable to assume that BF classification could be potentially assigned to any sample where the base-flow-to-total-flow ratio was greater than 50 percent. Therefore, this sample classification analysis was performed for each threshold value between 50 and 100 percent to see which threshold value resulted in the best correlation for both the BF and RO rating curves. The R^2 correlation value served as the performance measure for goodness of fit.

Table 4-22. Baseflow and storm-flow sediment and nutrient rating curves summary for Ward Creek (Tetra Tech 2007).

Constituent and Sample Type[1]		Number of Samples	Base-flow Threshold	Log of Intercept	Slope	R^2
Sediment	BF	77	98%	6.326	1.354	0.863
	RO	457	98%	7.473	1.769	0.811
Total Nitrogen	BF	69	99%	2.165	1.149	0.915
	RO	337	99%	2.609	1.144	0.880
Total Phosphorus	BF	90	96%	0.571	0.982	0.940
	RO	312	96%	1.339	1.211	0.829
Dissolved Inorganic Nitrogen	BF	76	98%	-0.213	1.066	0.907
	RO	328	98%	0.220	1.081	0.843
Dissolved Inorganic Phosphorus	BF	295	58%	-0.659	0.856	0.925
	RO	107	58%	-0.098	0.870	0.900

[1] BF indicates baseflow samples and RO indicates storm-flow samples (collected during runoff events)

The rating curves were used to develop loading estimates and summarized to produce seasonal trends and loading distributions. Figure 4-22 is an example of the results. As an independent validation of this methodology, dissolved organic nitrogen (DON) values were compared against independently computed fractions (Coats and Goldman 2001), and were found to be in agreement.

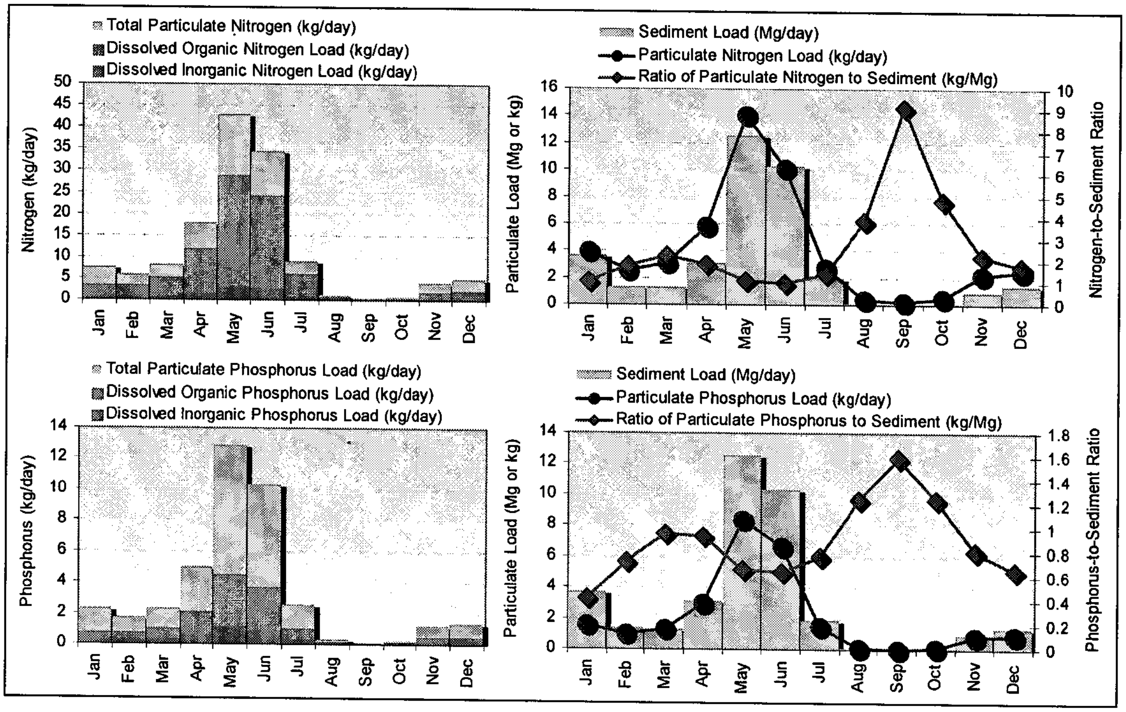

Figure 4-22. Seasonal nitrogen and phosphorus constituent distribution for Ward Creek water quality samples for data collected between 1972 and 2003, derived from hydrograph separation and regression (Tetra Tech 2007).

The insights gained from this statistical data 'mining' exercise provide guidance for selecting appropriate source loading parameters for a deterministic watershed simulation model. Some interesting observations from reviewing the results are presented below:

- About 70 percent of the total annual sediment, nitrogen and phosphorous loads are delivered to the streams during the snowmelt months of April, May and June.
- On average, 8.5 percent of TN is dissolved inorganic-N and 12 percent of TP is dissolved inorganic-P. In support of these modeling results, Coats and Goldman (2001) reported that dissolved inorganic-N was roughly 10 percent of TN. Also, analysis of the 1991-2004 LTIMP database for the 10 stream mouth stations showed that the ratio of soluble reactive-P was 18 ± 8 percent of TP.
- While the months of August, September and October yield the lowest amount of sediment and nutrients, the ratio of particulate nutrient mass to total sediment mass shows a distinct 2 to 4 times increase, suggesting that the organic matter in terms of percent composition of total sediment increases during these months; likely contributed in part as a result of increased attached algal growth/decay during the summer months.
- Comparison of total nitrogen distribution and loading to an independent analysis performed using the same dataset shows excellent agreement in estimated loads for Ward Creek (Coats and Goldman 2001, estimate about 1.5 kg-N/ha/yr for Ward Creek, compared to 1.6 kg-N/ha/yr for this analysis).

Model Parameterization by Land-use

Following the data 'mining' analysis, monthly variable baseflow and surface concentrations were directly computed using the various loading components and their associated flow volumes. Particulate nutrient mass was modeled as a sediment-associated fraction using the derived nutrient-to-sediment mass ratios.

Water quality parameters are specified at the land-use level for each subwatershed. The primary objective of this parameterization is to represent the influence and relative contribution of each upstream land-use on the total observed loads at the mouth of the tributary. The first step is to characterize the total runoff volumes for each land segment. This is done using the process-based hydrologic component of the Lake Tahoe Watershed Model, which uses hourly meteorological forcing data and land-segment specific hydrologic parameters derived by observation, estimation, and calibration. Each tributary outflow is evaluated to see how well it reflects the unique characteristics of its component watershed response. The second step is to determine and assign representative runoff concentrations for each land-use.

Stormwater runoff often represents a significant source of nutrients and sediment. Pollutants, such as nutrients, that have accumulated on watershed surfaces or are part of the soils within the watershed (subject to erosion) are readily transported by way of the stormwater drainage systems and/or overland flow during rain/snow melt events. Increases in impervious cover associated with urbanization (e.g., streets and parking lots) decrease the natural capacity to absorb rainfall and remove pollutants by filtering and treating the runoff through vegetative cover and the soil matrix. Urbanized areas in the Tahoe basin generate substantial pollutant concentrations (e.g. Reuter et al. 2001, Heyvaert et al. 2006). Additionally, there are typically higher runoff volumes and peak flow rates in developed urban areas due to greater impervious cover; i.e. less opportunity for infiltration. In general, decreased water quality treatment and increased stormwater runoff volumes and peak flow rates associated with urbanization increase sediment and nutrient loading (Schueler 1987).

Event mean concentrations (EMC) represent the average concentration of constituents in land-use runoff. EMCs for most urban land-uses were developed based upon stormwater monitoring information collected from 19 autosamplers distributed around the basin (Figure 4-23)(Heyvaert et al. 2007). At 10 of the 19 sites, continuous real-time data including specific conductance, water temperature, stage, and turbidity were conducted. The autosamplers were triggered by a predetermined stage height or preset volume. The height, volume, and frequency to which sampling is triggered differs at each site depending on typical site flow conditions. The relative land-use characteristics at each monitoring sites are shown in Figure 4-24. This stormwater monitoring program was conducted in water years (Oct 1st – Sept 30th) 2003 and 2004 as part of the Lake Tahoe TMDL research effort conducted by the DRI and UC Davis - TERC. Results are reported in Gunter 2005 and Coats et al. 2008. It proved to be very difficult to design the stormwater monitoring program to target each individual land-use. Flow was typically any combination of mixed land-uses since the impacted areas are relatively small.

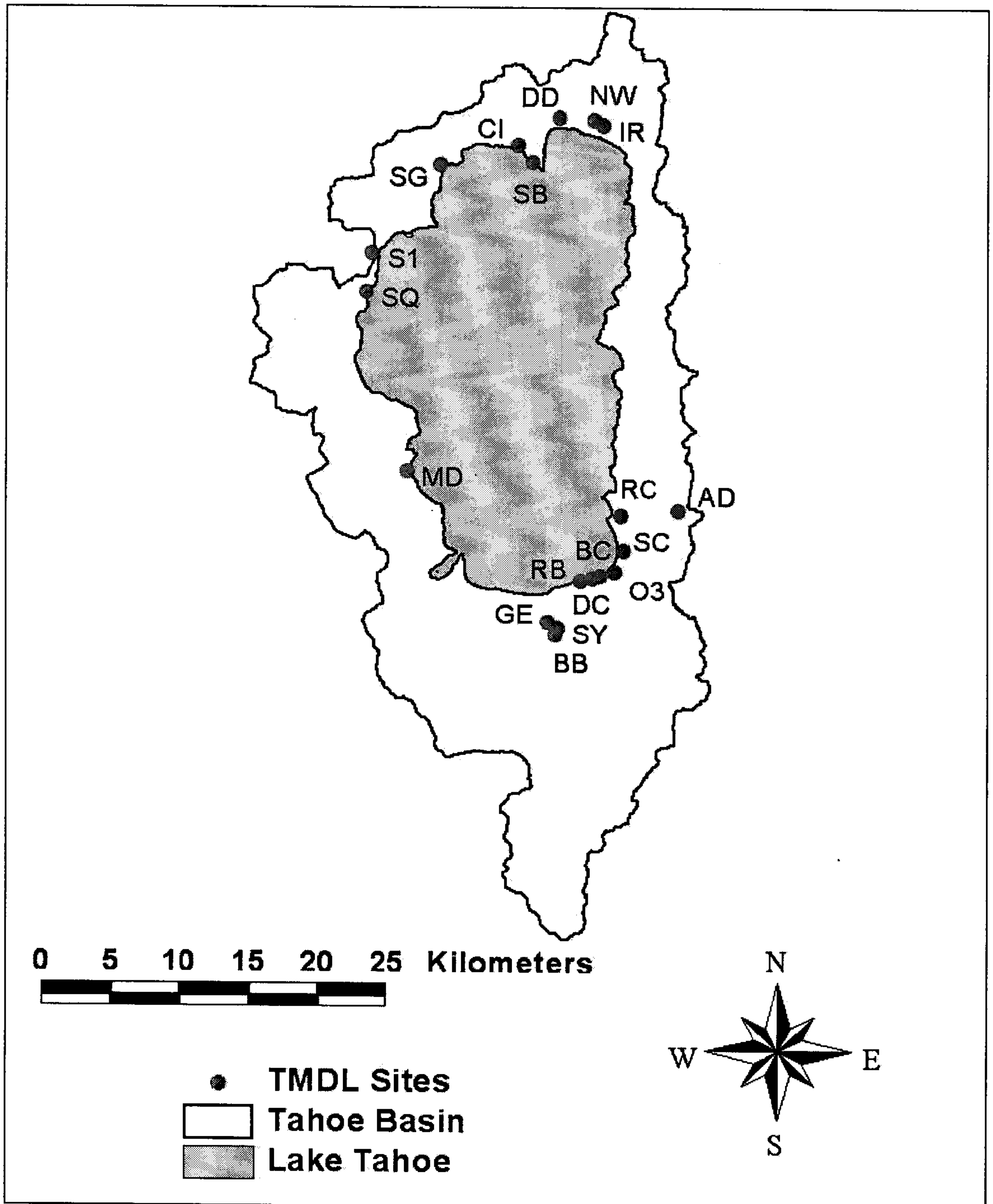

Figure 4-23. Location of TMDL stormwater monitoring sites during 2003-2004 (modified from Gunter 2005). [AD=Andria Drive, BB=Bonanza Avenue, BC=Bijou Creek, CI=Coon Street, DC=Don Cheapos, DD=Dale Drive, GE=Glorene and Eighth, IR=Incline Village Raley's, MD=Mountain Drive, NW=Northwood Boulevard, O3=Osgood Avenue, RB=Regan Beach, RC=Roundhill CDS, S1=Tahoe City Wetlands Treatment System, SB=Speedboat Avenue, SC=SLT Casinos, SG=Shivagiri, SQ=Sequoia Avenue, SY=SLT-Y]

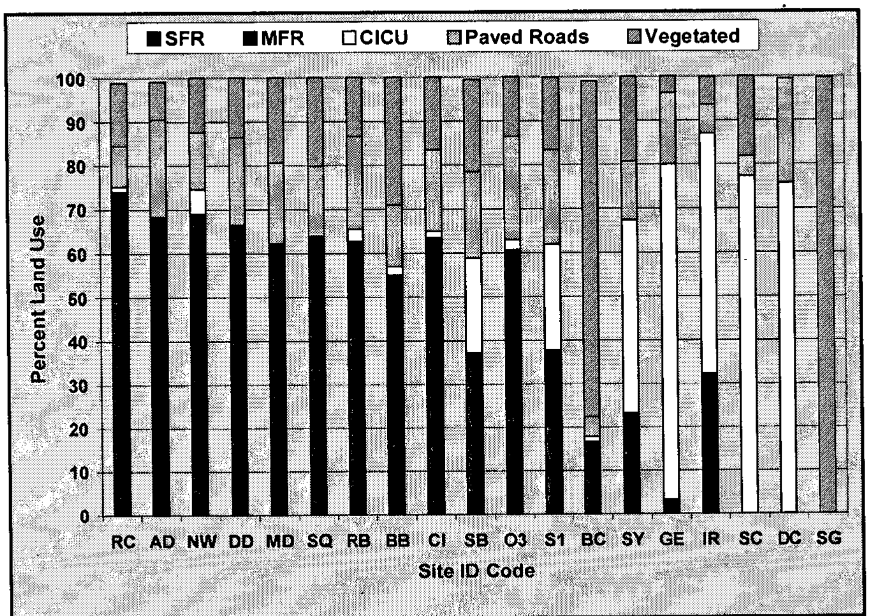

Figure 4-24. Relative land-use characteristics at each of the 19 autosampler locations used for stormwater monitoring. SFR – single family residential, MFR – multiple family residential, CICU – commercial industrial, communications and utilities, paved roads and vegetated undeveloped (Heyvaert et al. unpublished).

Reliable EMCs were obtained for the following land-uses; commercial, mixed urban, high density residential, and low density residential. While some data was collected from vegetated, undeveloped areas, the primary focus of this monitoring program was to collect information from urban areas. EMC for primary roads were collected by independent monitoring programs operated by Caltrans (2003) and NDOT (Jones et al. 2004). EMC data were not available for other, more specific land-uses (ski runs, vegetated recreational, vegetated turf, roads secondary, vegetated burned, vegetated harvest, and Vegetated EP1 - EP5). In some instances, relative evaluations between other land-uses were used to develop EMCs, while in other instances, available grab sample data, literature information, or in-stream concentrations were used to develop EMCs. After the initial EMC estimates by land-use were developed, a margin of safety of 20 percent was added. The following bullets describe how the initial target EMCs by land-use were obtained:

- Residential Single Family, Residential Multiple Family, and CICU, Pervious and Impervious – Concentrations were taken from EMC analysis of runoff data from the DRI/UC Davis-TERC Stormwater Monitoring Dataset (Gunter 2005). In this study, runoff mean concentrations were related to watershed characteristics and land-use through multiple linear regression analyses. The study showed that particulate species of nitrogen and phosphorus were the most abundant sources of nutrients in stormwater, and they were especially high in commercial land-uses. Population density and typical activities associated with these areas are directly related to increases in nutrient and sediment concentrations for residential land-uses (Gunter 2005). No distinction was made between runoff concentrations from pervious and impervious areas.

- Ski Runs Pervious – This land-use includes lands within otherwise vegetated areas for which trees have been cleared to create a run. The three ski areas in the watershed with available data, Heavenly, Homewood, and Diamond Peak, have very different runoff characteristics and, consequently, are modeled separately. The concentrations are based on stream data at each ski area, background values, and the area of the ski runs.

- Vegetated Recreational – This land-use includes lands that are primarily vegetated and are characterized by relatively low-intensity uses and small amounts of impervious coverage. These include the unpaved portions of campgrounds, visitor centers and day use areas. Final values calculated assume that the areas are represented by 40 percent roads, and 60 percent forest.

- Vegetated Turf - This land-use includes large turf areas with little impervious coverage, such as golf courses, large playing fields, and cemeteries, with potentially similar land management activities. EMCs are based on application ratios and land turf areas for golf course vs. residential. According to the USACE (2003) groundwater report, the ratio of fertilizer application for nitrogen and phosphorus for Golf Courses relative to Residential was approximately 2.5 to 1, assuming the Home Landscaping Guide instructions are followed, which is a reasonable assumption. With the assumption that most nitrogen/phosphorus runoff from residential land comes from fertilizer applied to lawns and the estimate of total residential areas to lawns is 1.25:1.0, these values represent 1.25 x 2.5 = 3.125 times the mean of Single Family Residential. Estimates do not account for infiltration of nitrogen and phosphorus. The recommended TSS concentration is based on the best professional judgment of the modelers.

- Roads Primary – EMCs were obtained from data in the Caltrans (2003) monitoring report and a report from NDOT and DRI that looked at highway stormwater runoff and BMP effectiveness on portions of SR 28 and US 50 in Nevada (Jones et al. 2004).

- Roads Secondary – No direct data was available for secondary roads. EMCs from this land-use are assumed to be the same as those developed/estimated for the multiple family residential land-use.

- Roads Unpaved – EMCs are based on data from McKinney Rubicon Rd USFS data. EMCs shown are the median of 20 samples taken from the road drainage. Independent calculation for this EMC, based on the Sierra Nevada Ecosystem Project (McGurk et al. 1996) sediment loadings by road slope, returned 955 mg/L for TSS.

- Vegetated Burned – These are areas that have been subject to controlled burns and/or wildfires during the 1996-2004 modeling time period. A six-year linear recession curve to zero-impact is used to compute the diminishing effects of the burn over time.

- Vegetated Harvest – These are lands that management agencies have thinned for the purpose of forest health and to reduce the spread of wildfire. The EMCs used are the same as unpaved roads, but the impact areas are adjusted based on the Equivalent Road Area obtained from USFS for each event. To account for the diminishing impact of the harvesting activity through time during the calibration years, a recession curve was used.

- Vegetated EP1 through EP5 – EMCs for each of the five erosion potential categories were initially estimated by running the model with all the land-uses set at their target EMCs described above, and performing a multi-regression optimization analysis resulting in the best estimate EMC for each of the five erosion potential categories.

Table 4-23 presents the final runoff EMCs that were developed for each of the land-uses. Figure 4-25 indicates that in most cases, the higher concentrations are associated with urban runoff as compared to those measured in the LTIMP streams.

Table 4-23. Derived EMCs for runoff by modeled land-use categories (mg/L).

Land-use Name	TN	DN	TP	DP	TSS
Residential_SFP	1.752	0.144	0.468	0.144	56.4
Residential_MFP	2.844	0.420	0.588	0.144	150.0
CICU-Pervious	2.472	0.293	0.702	0.078	296.4
Ski_Runs-Pervious	0.360	0.132	0.120	0.038	270.7
Veg_EP1	0.164	0.011	0.034	0.029	14.0
Veg_EP2	0.164	0.011	0.034	0.029	37.6
Veg_EP3	0.164	0.011	0.034	0.029	100.9
Veg_EP4	0.164	0.011	0.034	0.029	270.7
Veg_EP5	0.164	0.011	0.034	0.029	726.6
Veg_Recreational	1.035	0.012	0.629	0.209	459.6
Veg_Burned	2.340	0.014	1.524	0.480	1015.2
Veg_Harvest	2.340	0.014	1.524	0.480	1015.2
Veg_Turf	5.475	0.450	1.463	0.450	12.0
Water_Body	0.000	0.000	0.000	0.000	0.0
Residential_SFI	1.752	0.144	0.468	0.144	56.4
Residential_MFI	2.844	0.420	0.588	0.144	150.0
CICU-Impervious	2.472	0.294	0.702	0.078	296.4
Roads_Primary	3.924	0.720	1.980	0.096	951.6
Roads_Secondary	2.844	0.420	0.588	0.144	150.0
Roads_Unpaved	2.340	0.014	1.524	0.480	1015.2

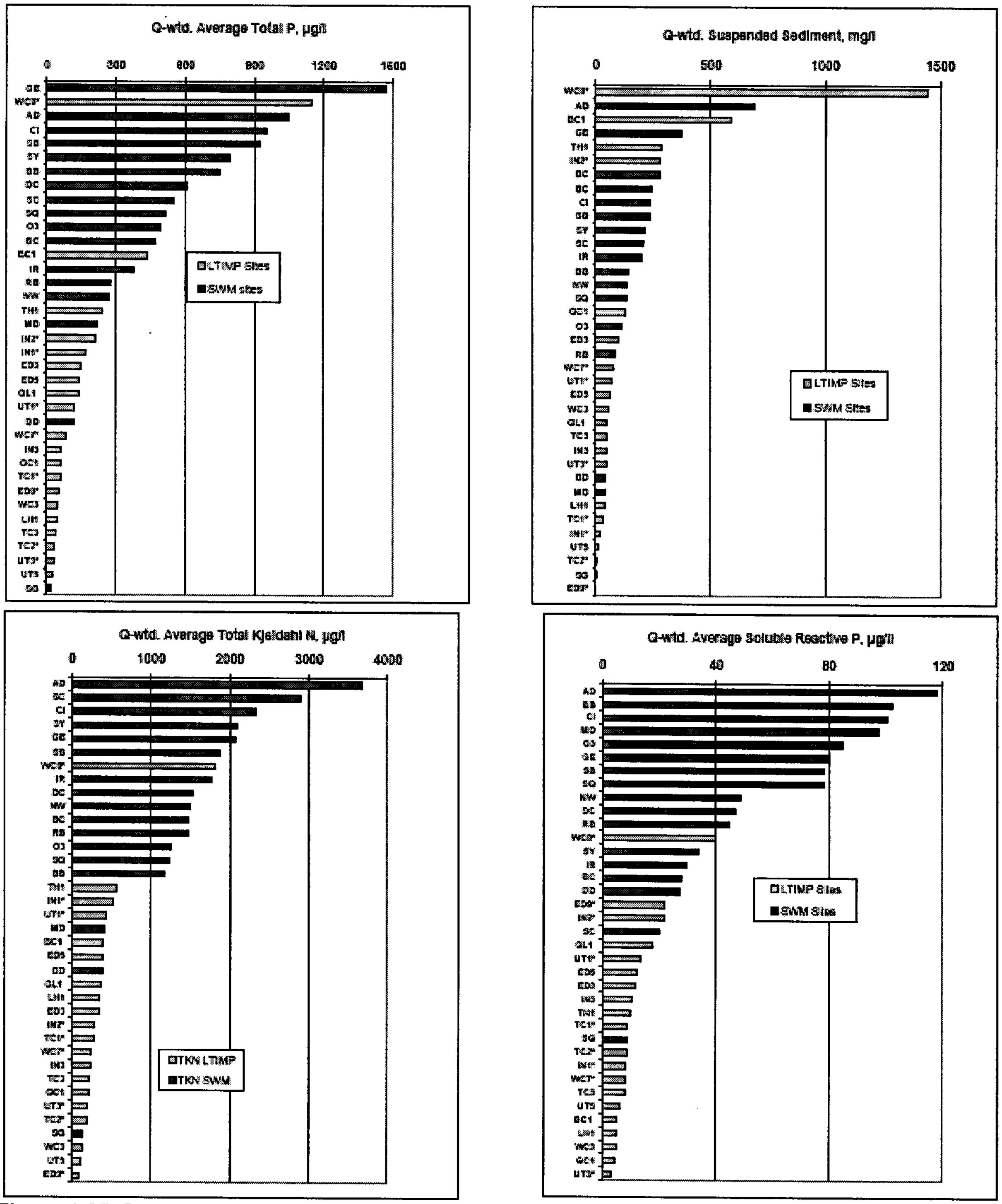

Figure 4-25. Summary of flow-weighted (Q-wtd.) concentrations for TP, TSS, total Kjeldahl-N and soluble-P for stormwater monitoring sites and LTIMP (mouth) sites for period 2003-2004 (Coats et al. 2008).

In addition to the EMCs, the fraction of the TSS comprised of fine sediment (< 63 µm) was estimated for each urban land-use category using data collected for the period 2003-2004 as part of the Lake Tahoe TMDL Stormwater Study (Hayvaert et. al 2007). The same urban sediment distribution was applied to all land-uses of the same type in all subwatersheds. The remaining non-urban land-uses were assigned a uniform distribution of fine sediment based on in-stream sediment distributions that varied by subwatershed. Table 4-24 shows the fine sediment distributions by land-use and subwatershed.

Table 4-24. Percent fines by land-use and subwatershed as applied in the Lake Tahoe Watershed Model (Tetra Tech 2007).

Land-use Type	Land-use Name or Subwatershed	Runoff Fines Distribution		
		(< 63 µm)	(20 - 63 µm)	(< 20 µm)
Urban	Residential_SF	76.3%	40.6%	35.7%
Urban	Residential_MF	88.4%	30.7%	57.7%
Urban	CICU	85.4%	22.3%	63.1%
Urban	Roads_Primary	85.4%	22.3%	63.1%
Urban	Roads_Secondary	85.4%	22.3%	63.1%
Non-Urban	Third Creek	31.0%	21.5%	9.5%
Non-Urban	Incline Creek	67.0%	46.6%	20.4%
Non-Urban	Glenbrook Creek	80.0%	55.4%	24.6%
Non-Urban	Logan House Creek	75.0%	51.6%	23.4%
Non-Urban	Edgewood Creek	59.0%	41.2%	17.8%
Non-Urban	General Creek	29.0%	20.3%	8.7%
Non-Urban	Blackwood Creek	45.0%	31.4%	13.6%
Non-Urban	Ward Creek	47.0%	32.3%	14.7%
Non-Urban	Trout Creek	38.0%	26.3%	11.7%
Non-Urban	Upper Truckee River	44.0%	30.6%	13.4%

Water Quality Calibration Process

Once the water quality parameters were initially set-up in the model, the model was run and the results of the annual average loads by calibration watershed were compared with the annual loads obtained using the available LTIMP data. After this initial comparison was made, two things were noted. First, the modeled fine sediment loads were too low for those areas with a large percent of volcanic soils and second, fine sediment loads were too high for those areas dominated by granitic soils. In a series of papers by Grismer and Hogan (2004, 2005a, b) - who studied soil erosion in the Lake Tahoe basin using a portable rainfall runoff simulator – it was reported that runoff rates, sediment concentrations and sediment yields were greater from volcanic soils as compared to that from granitic soils for nearly all vegetated cover conditions tested.

To account for this difference, a simple regression model was developed that relates the required multiplying factor for the pervious land-uses and the percent volcanic soils in the watershed. This regression is presented in Figure 4-26. Each point in the graph represents a calibration watershed (from the Lake Tahoe Interagency Monitoring Program). It can be observed that the higher the fraction of volcanic soils in the watershed, the higher the multiple required for the TSS EMCs. Given that Grismer and Hogan (2004) found that sediment yield from bare volcanic soils ranged from 2 - 12 grams of sediment per square meter per milimeter of applied water as compared to 0.3-3 grams of sediment per square meter per milimeter of applied water for granitic soils, the range of multipliers determoned in Figure 4-26 appears reasonable.

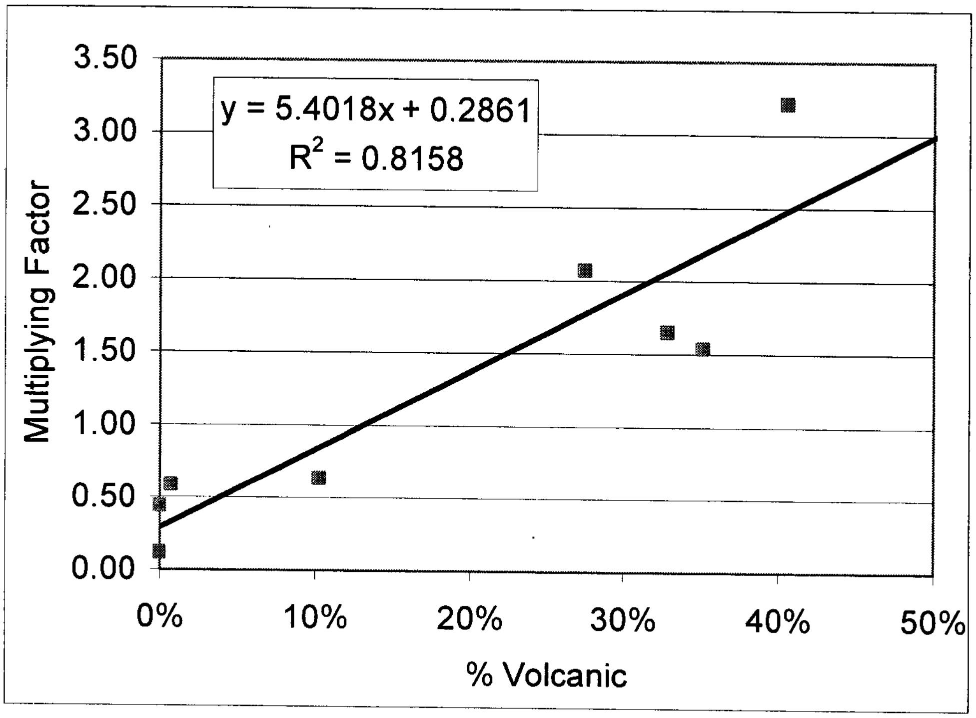

Figure 4-26. EMC multiplying factor for pervious land-uses relative to percent volcanic (Tetra Tech 2007).

After the soil variability was taken into account, the model was run again, and a second observation was made. This observation was related to the differences in the fine-load estimates by quadrant of the watershed. The model's estimate was low for the northern and western quadrants and high for the southern and eastern ones. This error was minimized by applying the following scaling factors to the EMCs for all land-uses (Table 4-25). Similar scaling factors were also derived for total nitrogen and total phosphorus following the quadrant method. Direct field monitoring data from the LTIMP database were used in the development of these scaling factors.

Table 4-25. Scaling factor for EMCs by quadrant (modified from Tetra Tech 2007).

Quad ID	Quad Name	Ratio TSS	Ratio nitrogen	Ratio phosphorus
1	North	1.59	0.986	0.483
2	East	0.11	0.409	0.628
3	South	0.74	0.823	0.757
4	West	1.45	1.535	1.558

A summary of the results of the water quality calibration is shown in Table 4-26, Table 4-27, and Table 4-28.

Table 4-26. Results of water quality calibration for upland fine sediment (modified from Tetra Tech 2007).

Name	Overland Flow, 1000 m^3/year	Baseflow, 1000 m^3/year	Modeled: Upland Fines (metric tons/year)	Target:* Upland Fines (metric tons/year)	Fines Ratio (target / modeled)
Third Creek	1,070	5,600	190	229	**1.21**
Incline Creek	1,270	6,380	357	318	**0.89**
Glenbrook Creek	587	3,220	25	17	**0.71**
Logan House Creek	258	1,210	4	7	**2.02**
Edgewood Creek	1,430	2,630	21	24	**1.16**
General Creek	3,390	11,700	60	62	**1.04**
Blackwood Creek	3,730	25,700	837	1,150	**1.38**
Ward Creek	4,980	18,900	1,430	1,110	**0.78**
Trout Creek	3,980	28,400	205	189	**0.92**
Upper Truckee River	22,900	78,800	1,010	1,030	**1.02**
TOTAL	**43,600**	**183,000**	**4,140**	**4,140**	**1.00**

* Upland targets adjusted to account for net transport losses

Table 4-27. Results of water quality calibration for total nitrogen (modified from Tetra Tech 2007).

Name	Overland Flow, 1000 m^3/year	Baseflow, 1000 m^3/year	Modeled: Total Nitrogen (kg/year)	Target: Total Nitrogen (kg/year)	Ratio TN (target / modeled)
Third Creek	1,070	5,600	2,820	3,930	**1.39**
Incline Creek	1,270	6,380	3,300	2,190	**0.66**
Glenbrook Creek	587	3,220	383	638	**1.67**
Logan House Creek	258	1,210	157	241	**1.53**
Edgewood Creek	1,430	2,630	1,370	1,030	**0.75**
General Creek	3,390	11,700	3,150	3,160	**1.01**
Blackwood Creek	3,730	25,700	8,400	9,170	**1.09**
Ward Creek	4,980	18,900	6,440	5,660	**0.88**
Trout Creek	3,980	28,400	6,540	5,390	**0.82**
Upper Truckee River	22,900	78,800	24,100	25,300	**1.05**
TOTAL	**43,600**	**183,000**	**56,700**	**56,700**	**1.00**

Table 4-28. Results of water quality calibration for total phosphorus (modified from Tetra Tech 2007).

Name	Overland Flow 1000 m^3/year	Baseflow 1000 m^3/year	Modeled: Total Phosphorus (kg/year)	Target: Total Phosphorus (kg/year)	Ratio TP (target / modeled)
Third Creek	1,070	5,600	843	1,170	**1.38**
Incline Creek	1,270	6,380	877	553	**0.63**
Glenbrook Creek	587	3,220	143	137	**0.96**
Logan House Creek	258	1,210	26	21	**0.80**
Edgewood Creek	1,430	2,630	203	214	**1.05**
General Creek	3,390	11,700	517	398	**0.77**
Blackwood Creek	3,730	25,700	2,320	2,710	**1.17**
Ward Creek	4,980	18,900	2,030	1,760	**0.87**
Trout Creek	3,980	28,400	1,000	954	**0.95**
Upper Truckee River	22,900	78,800	4,110	4,160	**1.01**
TOTAL	**43,600**	**183,000**	**12,100**	**12,100**	**1.00**

Once the upland model was calibrated, a summary of average annual upland loads was obtained for each modeled stream. Simon (2006) provided an estimate of total fine sediment load vs. channel fine sediment load for each stream. From this information, the ratio of channel fines to total fines was applied to the modeled upland load as follows to obtain an estimate of total fine sediment loads for all streams:

Total Fine Sediment Load = Upland Fines Load / (1 – [Channel Fines / Total Fines])

From there, the channel fine sediment load becomes:

Channel Fines Load = Total Fines Load x [Channel Fines / Total Fines]

Time series comparison revealed that the timing of streambank erosion was not linearly related to the timing of upland fines. Therefore, it was not representative to simply multiply the modeled upland fines load by the stream fines ratio. However, streambank erosion frequency appeared to vary closely with streamflow. Assuming a linear relationship between streambank erosion and stream flow, estimated channel loads were distributed according to modeled flows from the Lake Tahoe Watershed Model to generate time series of channel fines sediments. This time series was superimposed over the original upland fines time series, resulting in a complete total fines time series representation.

After selecting appropriate water quality parameters for the Lake Tahoe Watershed Model, modeled results were compared against both the observed data points. Figure 4-27, Figure 4-28, and Figure 4-29 show Lake Tahoe Watershed Model results versus observed data for TSS, TN and TP for Ward Creek which is used as an example.

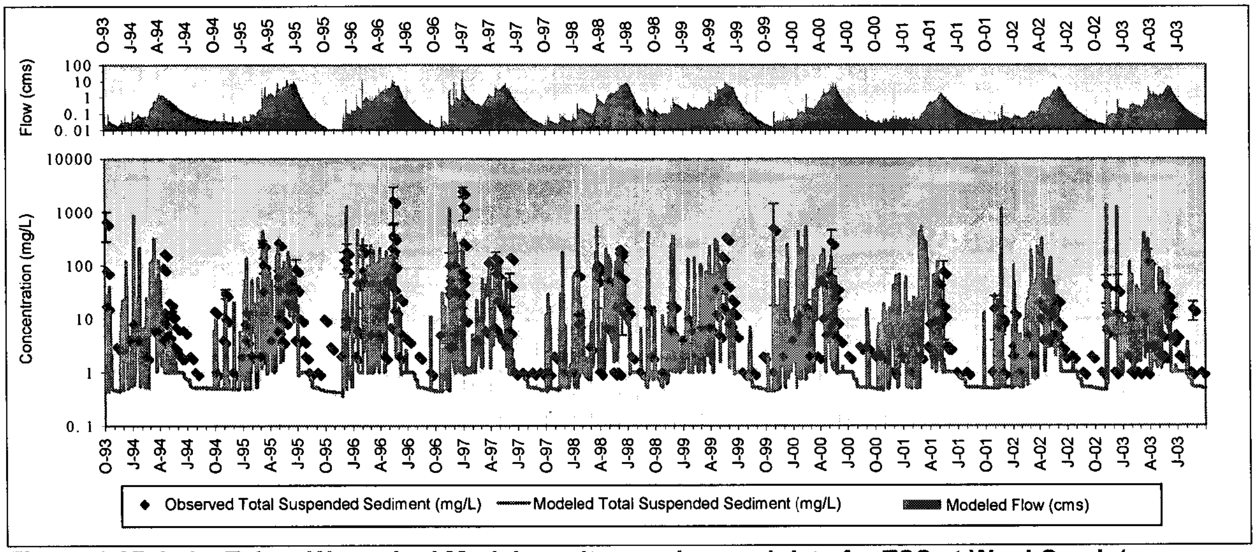

Figure 4-27. Lake Tahoe Watershed Model results vs. observed data for TSS at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

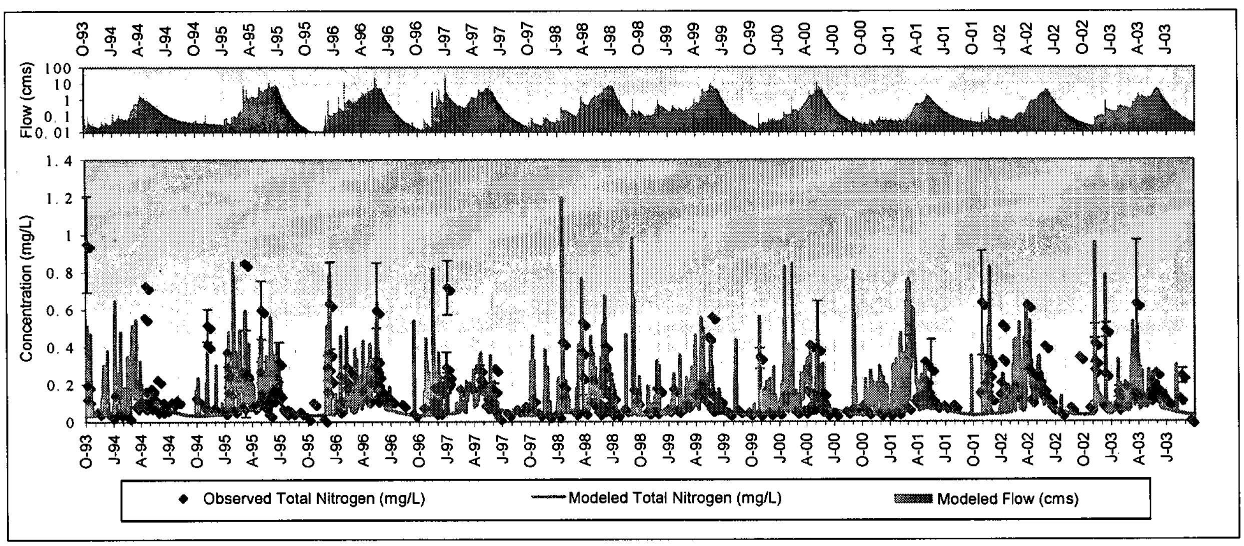

Figure 4-28. Lake Tahoe Watershed Model results vs. observed data for TN at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

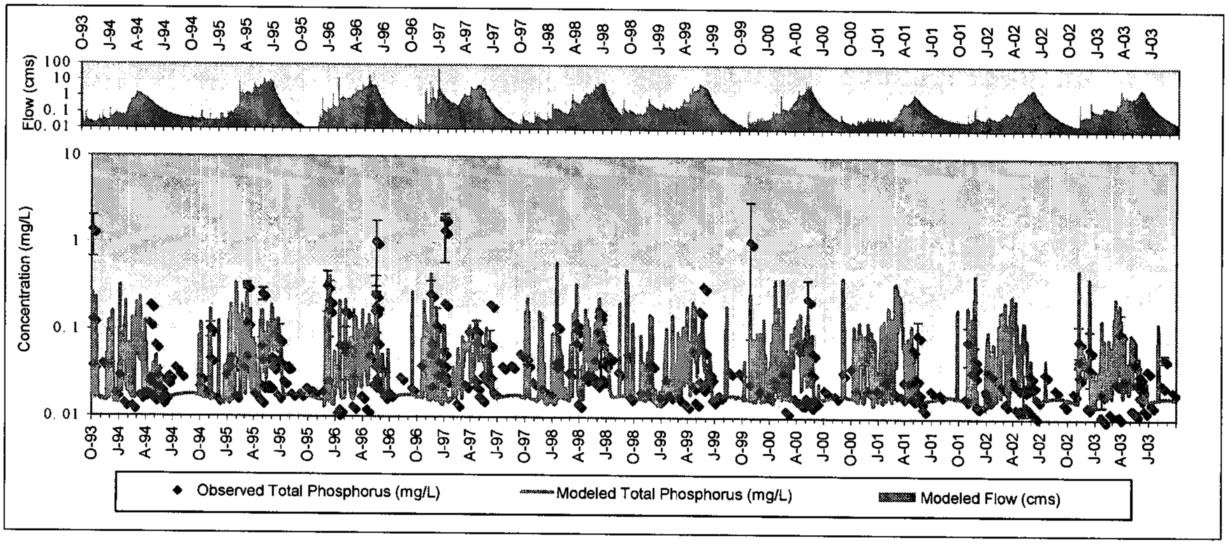

Figure 4-29. Lake Tahoe Watershed Model results vs. observed data for TP at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

4.3.6 Results

This section is not intended to provide an exhaustive description and discussion of the model output. Rather, the objective herein is to (1) present a summary of the model output over the 1994-2004 period, (2) provide flow volume, TSS, fine sediment (< 63 µm), TN and TP output for each of the watersheds and modeled intervening zone units, and (3) distinguish between urban and non-urban areas, and specific land-uses when considering loads. Some general observations are described below regarding the influence of elevation, location, and land-use on the model predicted results for water yield, sediment, and nutrient loads. The period 1994-2004 was characterized by a wide range of precipitation conditions including very wet and very dry years. The range of annual precipitation amounts (as measured at Tahoe City as part of the approximately 100 year data record) was 17 – 61 inches with a mean ± standard deviation of 36 ± 15 inches. For reference the lowest annual precipitation measured at this location was approximately nine inches in 1977 and the highest annual precipitation was 69 inches in 1982. Mean annual precipitation at the Tahoe City location since 1910 has been approximately 32 inches.

General observations

Elevation

Elevation has the biggest effect on predicted water yield. Higher elevations tend to receive higher amounts of snowfalls. In general, for subwatersheds in the same region, unit-area flow increases as elevation increases. Total flow volume, location, and land-use are factors that directly influence model-predicted loads.

Location

The Lake Tahoe watershed has distinct orographic features that vary spatially. By categorizing the watershed into north, south, east, and west quadrants; one can see distinct spatially variable patterns. Unit area water yield varies by quadrant. The west quadrant is wettest while the east is the driest. The prevailing weather patterns in the basin are significantly influenced by the topographic relief. If one considers two subwatersheds with the same elevation on the west side and east side, the western subwatershed will typically experience over two times the volume of precipitation and water yield as its eastern counterpart. Total flow volume has a direct effect on the predicted model load.

Land-use

Table 4-31 shows the percent of total contribution for Upland TSS, Upland Fines, Nitrogen and Phosphorus from each of the 20 land-use categories. Marked in bold are values for which a single land-use category contributes greater than 10 percent of the total load. A cursory review shows a fairly consistent correlation of flow yield with area. Table 4-31 also shows that the largest contributors are generally vegetated areas and roads. While roads represent a relatively small amount of area, they are impervious surfaces which tend to serve as conduits for flow from surrounding areas. As modeled, concentrations from road surfaces are higher than those from other pervious and impervious areas. In general, while urban areas represent a relatively small percentage of the watershed area, they exhibit a disproportionately higher level of fine sediment and nutrient loads. Finally, it's noteworthy to mention that the "Water_Body" land-use was retained in the land-use list to complete the water balance. There are several smaller high elevation lakes that were not explicitly modeled. The associated water surface areas contribute flow from direct precipitation, but do not directly generate pollutant loads.

Flow volumes

A summary of average flow volume from each of the modeled intervening zones and individual streams over the 1994-2004 period is given in Table 4-29. The total annual flow volume was modeled at 4.48×10^8 m^3 with approximately 25 percent entering the stream directly by flow over the land surface. The remaining approximately 75 percent infiltrates through the shallow soils prior to entering the stream (i.e. termed baseflow). As presented in Table 4-17 the Lake Tahoe Watershed Model (LSPC) estimate of streamflow agreed well with previous estimates. The largest individual stream contributor to total flow was the Upper Truckee River at 25 percent of total stream contribution. Combined, the Upper Truckee River, Trout Creek, Blackwood Creek and Ward Creek accounted for 46 percent of the total stream flow. Flow from the intervening zones contributed 10 percent of the total flow volume with 90 percent coming from stream discharge. This estimate is nearly identical to that made by Marjanovic (1989) and used by Reuter et al. (2003) in the initial estimate of pollutant loading from intervening zones.

Table 4-29. Summary of annual surface, base and total flow volumes by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	1.13E+06	1.66E+06	2.80E+06
IVZ2000	2000	7.55E+05	3.63E+06	4.39E+06
IVZ3000	3000	1.42E+06	3.45E+06	4.87E+06
IVZ4000	4000	1.99E+06	2.21E+06	4.21E+06
IVZ5000	5000	2.20E+06	2.62E+06	4.81E+06
IVZ6000	6000	7.68E+05	3.99E+06	4.75E+06
IVZ6001	6001	8.05E+05	1.42E+06	2.23E+06
IVZ7000	7000	1.61E+06	2.86E+06	4.47E+06
IVZ8000	8000	1.56E+06	2.96E+06	4.51E+06
IVZ9000	9000	1.47E+06	4.79E+06	6.26E+06
TOTAL		1.37E+07	2.96E+07	4.33E+07
STREAM FLOW				
MILL CREEK	1010	3.69E+05	1.92E+06	2.29E+06
INCLINE CREEK	1020	1.27E+06	6.38E+06	7.64E+06
THIRD CREEK	1030	1.07E+06	5.60E+06	6.67E+06
WOOD CREEK	1040	3.87E+05	1.81E+06	2.20E+06
BURNT CEDAR CREEK	1050	1.93E+05	2.23E+05	4.16E+05
SECOND CREEK	1060	1.96E+05	1.29E+06	1.49E+06
FIRST CREEK	1070	1.84E+05	1.68E+06	1.87E+06
SLAUGHTER HOUSE	2010	9.35E+05	3.73E+06	4.67E+06
BLISS CREEK	2020	8.24E+04	4.27E+05	5.09E+05
SECRET HARBOR CREEK	2030	4.17E+05	2.68E+06	3.10E+06
MARLETTE CREEK	2040	1.54E+06	3.31E+06	4.85E+06
BONPLAND	2050	1.10E+05	6.73E+05	7.83E+05
TUNNEL CREEK	2060	1.09E+05	1.22E+06	1.33E+06
MCFAUL CREEK	3010	5.11E+05	2.12E+06	2.63E+06
ZEPHYR CREEK	3020	2.22E+05	9.55E+05	1.18E+06
NORTH ZEPHYR CREEK	3030	3.16E+05	1.51E+06	1.83E+06
LINCOLN CREEK	3040	2.89E+05	1.43E+06	1.72E+06
CAVE ROCK	3050	9.91E+04	4.16E+05	5.15E+05
LOGAN HOUSE CREEK	3060	2.58E+05	1.21E+06	1.46E+06
NORTH LOGAN HOUSE CREEK	3070	1.34E+05	8.40E+05	9.74E+05
GLENBROOK CREEK	3080	5.87E+05	3.22E+06	3.81E+06
BIJOU CREEK	4010	7.66E+05	1.45E+06	2.22E+06
EDGEWOOD CREEK	4020	1.43E+06	2.63E+06	4.06E+06
BURKE CREEK	4030	4.20E+05	1.79E+06	2.21E+06
UPPER TRUCKEE RIVER	5010	2.29E+07	7.88E+07	1.02E+08

Tributary	OUTLET SWS	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
TROUT CREEK	5050	3.98E+06	2.84E+07	3.24E+07
GENERAL CREEK	6010	3.39E+06	1.17E+07	1.51E+07
MEEKS	6020	4.13E+06	1.25E+07	1.67E+07
SIERRA CREEK	6030	4.39E+05	1.33E+06	1.77E+06
LONELY GULCH CREEK	6040	5.73E+05	1.64E+06	2.21E+06
PARADISE FLAT	6050	2.95E+05	9.55E+05	1.25E+06
RUBICON CREEK	6060	1.38E+06	4.37E+06	5.75E+06
EAGLE CREEK	6080	2.35E+06	1.01E+07	1.25E+07
CASCADE CREEK	6090	2.37E+06	6.53E+06	8.90E+06
TALLAC CREEK	6100	6.30E+05	3.35E+06	3.98E+06
TAYLOR CREEK	6110	1.78E+07	2.77E+07	4.55E+07
UNNAMED CK	6120	1.46E+05	3.97E+05	5.42E+05
BLACKWOOD CREEK	7010	3.73E+06	2.57E+07	2.94E+07
MADDEN CREEK	7020	1.09E+06	3.21E+06	4.29E+06
HOMEWOOD CREEK	7030	5.62E+05	1.57E+06	2.13E+06
QUAIL LAKE CREEK	7040	7.73E+05	2.23E+06	3.00E+06
MKINNEY CREEK	7050	2.62E+06	7.10E+06	9.72E+06
DOLLAR CREEK	8010	9.17E+04	9.58E+05	1.05E+06
UNNAMED CK LAKE FOREST 1	8020	2.15E+05	5.62E+05	7.77E+05
UNNAMED CK LAKE FOREST 2	8030	1.13E+05	8.78E+05	9.91E+05
BURTON CREEK	8040	2.58E+05	4.57E+06	4.83E+06
TAHOE STATE PARK	8050	8.43E+04	9.11E+05	9.95E+05
WARD CREEK	8060	4.98E+06	1.89E+07	2.39E+07
KINGS BEACH	9010	9.47E+04	3.62E+05	4.57E+05
GRIFF CREEK	9020	2.72E+05	3.74E+06	4.01E+06
TAHOE VISTA	9030	5.60E+05	3.97E+06	4.52E+06
CARNELIAN CANYON	9040	2.25E+05	2.63E+06	2.86E+06
CARNELIAN BAY CREEK	9050	4.89E+04	7.71E+05	8.20E+05
WATSON	9060	1.27E+05	1.94E+06	2.07E+06
TOTAL		8.81E+07	3.16E+0	4.05E+08
GRAND TOTAL		1.02E+08	3.46E+08	4.48E+08
CONTRIBUTION FROM IZ		13%	9%	10%
CONTRIBUTION FROM STREAMS		87%	91%	90%

The contribution of urban land-use areas to total flow volume was also calculated to be 10 percent (Table 4-30). This is coincidentally the same percentage contributed by intervening zones; however, the two are not directly related since the percent urban area in the intervening zones ranges from 3 percent in IZ 6000 to 72 percent in IZ 1000. Table 4-30 also shows the contributions by specific land-use category as does Figure 4-30. By far the largest flow volume came from the vegetated land-use that was made up of the five erosion potential sub-units (EP1-EP5). Flow volume from this source was 83 percent of total (Table 4-31). The next largest contributor was the combination of pervious plus impervious single family residential parcels (5 percent of total flow volume). It is interesting that a minimal volume of the non-urban flow entered via surface flow (6 percent), while for the parcels in the urban area this value was 4-times higher at 25 percent. This reflects both the higher proportion of impervious area in the urban setting and the good infiltration capacity of native Tahoe basin soils.

Table 4-30. Summary of annual surface, base and total flow volumes by land-use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent mean over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
U	Residential_SFP	2.61E+06	1.44E+07	1.70E+07
U	Residential_MFP	4.65E+05	3.37E+06	3.84E+06
U	CICU-Pervious	3.70E+05	2.76E+06	3.13E+06
U	Residential_SFI	5.74E+06	0.00E+00	5.74E+06
U	Residential_MFI	2.24E+06	0.00E+00	2.24E+06
U	CICU-Impervious	3.04E+06	0.00E+00	3.04E+06
U	Roads_Primary	1.81E+06	0.00E+00	1.81E+06
U	Roads_Secondary	8.97E+06	0.00E+00	8.79E+06
NU	Ski_Runs-Pervious	8.19E+05	2.41E+06	3.23E+06
NU	Veg_EP1	3.35E+06	2.03E+07	2.37E+07
NU	Veg_EP2	2.68E+07	1.57E+08	1.84E+08
NU	Veg_EP3	1.87E+07	1.02E+08	1.21E+08
NU	Veg_EP4	6.07E+06	3.79E+07	4.40E+07
NU	Veg_EP5	2.60E+05	1.25E+06	1.51E+06
NU	Veg_Recreational	1.27E+05	6.07E+05	7.34E+05
NU	Veg_Burned	2.01E+05	8.61E+05	1.06E+06
NU	Veg_Harvest	9.37E+04	6.64E+05	7.58E+05
NU	Veg_Turf	2.19E+05	1.72E+06	1.94E+06
NU	Water_Body	1.98E+07	0.00E+00	1.98E+07
NU	Roads_Unpaved	1.64E+05	6.88E+05	8.52E+05
U	**TOTAL FLOW**	**2.52E+07**	**2.05E+07**	**4.58E+07**
NU	**TOTAL FLOW**	**7.66E+07**	**3.25E+08**	**4.02E+08**
	GRAND TOTAL	1.02E+08	3.46E+08	4.48E+08
	CONTRIBUTION FROM URBAN	25%	6%	10%
	CONTRIBUTION FROM NON-URBAN	75%	94%	90%

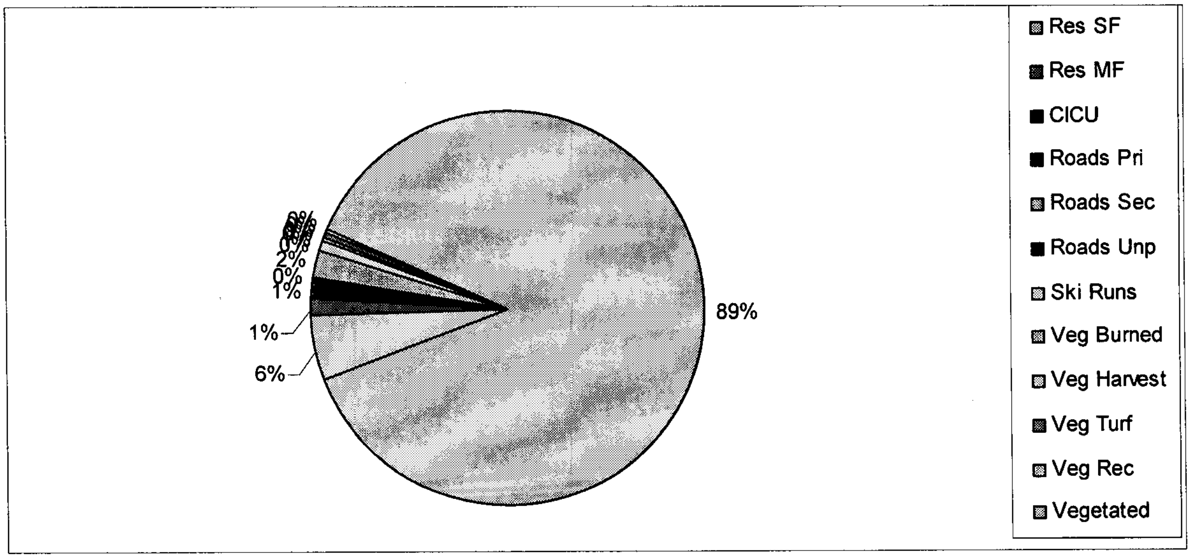

Figure 4-30. Relative contribution of major land-use types to total flow volume during the 1994-2004 model calibration/validation period (Tetra Tech 2007).

Table 4-31. Land-use area distribution and percent contribution to the model predicted outputs (Tetra Tech unpublished).

Land-use	Area	Flow	Upland TSS	Upland Fines (>63µm)	Total Nitrogen	Total Phosphorus
Residential_SFP	4.0%	3.8%	1.7%	2.3%	5.4%	7.5%
Residential_MFP	1.0%	0.9%	1.3%	1.9%	1.5%	2.2%
CICU-Pervious	0.9%	0.7%	1.3%	1.9%	1.0%	1.5%
Ski_Runs-Pervious	0.5%	0.7%	4.1%	2.5%	0.6%	1.3%
Veg_EP1	5.7%	5.2%	0.1%	0.1%	2.3%	1.4%
Veg_EP2	**46.3%**	**41.1%**	4.0%	3.2%	**20.9%**	**13.4%**
Veg_EP3	**26.1%**	**27.0%**	**17.6%**	**13.5%**	**16.4%**	**12.4%**
Veg_EP4	8.9%	9.7%	**33.1%**	**25.9%**	6.4%	6.3%
Veg_EP5	0.2%	0.3%	4.0%	3.2%	0.2%	0.4%
Veg_Recreational	0.2%	0.2%	0.2%	0.2%	0.2%	0.3%
Veg_Burned	0.2%	0.2%	1.0%	0.8%	0.4%	0.8%
Veg_Harvest	0.2%	0.2%	0.8%	0.6%	0.2%	0.5%
Veg_Turf	0.5%	0.4%	0.0%	0.0%	0.9%	2.0%
Water_Body	1.7%	n/a	n/a	n/a	n/a	n/a
Residential_SFI	0.9%	1.3%	2.0%	2.7%	7.6%	8.4%
Residential_MFI	0.4%	0.5%	2.3%	3.5%	4.8%	4.0%
CICU-Impervious	0.5%	0.7%	5.0%	7.4%	5.2%	5.3%
Roads_Primary	0.3%	0.4%	**10.8%**	**16.2%**	5.4%	**12.2%**
Roads_Secondary	1.3%	2.1%	8.6%	**12.9%**	**20.2%**	**18.1%**
Roads_Unpaved	0.2%	0.2%	2.0%	1.4%	0.4%	2.0%

Figure 4-31 shows the higher unit-area flows (i.e. flow volume per area of land surface) along the west shore.

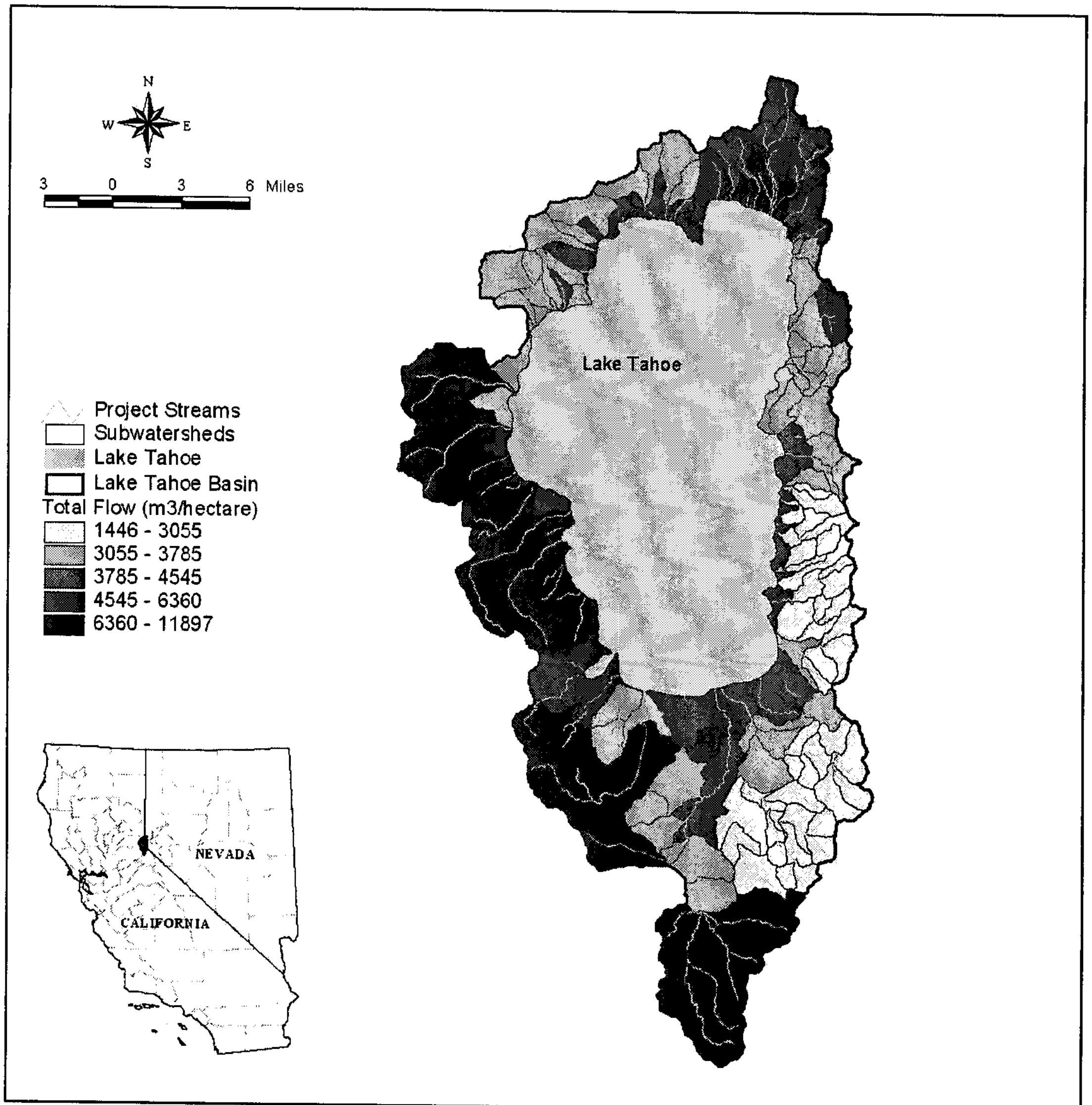

Figure 4-31. Unit-area annual water yield (m^3/ha) by subwatershed (Tetra Tech 2007).

Suspended sediment

Summary results from the Lake Tahoe Watershed Model for sediment loads from upland TSS, upland fines (< 63 µm), channel fines (< 63 µm) and total fines (< 63 µm expressed as the sum of upland and channel) are given in Table 4-32. Values designated as upland loads do not include sediment from stream channel erosion. Total upland TSS over the 1994-2004 period of record was nearly 17,000 metric tons per year with 83 percent coming from overland flow into streams and 17 percent from intervening zones. Of the total upland TSS load (streams + intervening zones), an estimated 9,100 metric tons or approximately 65 percent were in the < 63 µm size range. For the streams, approximately 50 percent of the TSS load was < 63 µm while that proportion increased to 75 percent within the intervening zones. When this same comparison is made between urban and non-urban areas the difference is even more pronounced with approximately 85 percent of the TSS load from urban land-uses associated with the < 63 µm size class. The contribution of upland fines to upland TSS in the non-urban areas was only 40 percent. This demonstrates the importance of upland fine sediment loading from urban areas. Overall, 31 percent of the upland TSS load (16,921 metric tons/year) came from urban sources while approximately 50 percent of the upland fines came from urban land-uses (Table 4-33).

Channel fines come only from stream channels, therefore values for intervening zones are not applicable. It was estimated that a total of 3,768 metric tons of fine sediment (< 63 µm) came from this source. This represents nearly 30 percent of the 12,872 metric tons/year load of total fines. The contribution of upland fines (9,100 metric tons/year) represents the remaining 70 percent of the total fines load (Table 4-32).

Table 4-32. Summary of annual upland TSS, upland fines, channel fines and total fines loads by watershed as determined using the Lake Tahoe Watershed Model. Channel fines were not explicitly modeled using the Lake Tahoe Watershed Model (see text on model calibration). Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
INTERVENING ZONE LOAD					
IVZ1000	1000	435	336	NA	336
IVZ2000	2000	114	97	NA	97
IVZ3000	3000	28	23	NA	23
IVZ4000	4000	292	248	NA	248
IVZ5000	5000	150	122	NA	122
IVZ6000	6000	122	96	NA	96
IVZ6001	6001	129	103	NA	103
IVZ7000	7000	469	304	NA	304
IVZ8000	8000	524	405	NA	405
IVZ9000	9000	679	468	NA	468
TOTAL		2942	2202	NA	2202
STREAM LOAD					
MILL CREEK	1010	114	94	0	94
INCLINE CREEK	1020	546	420	16	436
THIRD CREEK	1030	292	211	23	234
WOOD CREEK	1040	98	70	0	71
BURNT CEDAR CREEK	1050	80	60	4	64
SECOND CREEK	1060	51	26	0	26
FIRST CREEK	1070	79	29	0	30

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
SLAUGHTER HOUSE	2010	11	9	1	10
BLISS CREEK	2020	10	8	0	9
SECRET HARBOR CREEK	2030	28	23	0	23
MARLETTE CREEK	2040	28	23	2	25
BONPLAND	2050	3	2	0	2
TUNNEL CREEK	2060	4	3	0	3
MCFAUL CREEK	3010	2	1	0	2
ZEPHYR CREEK	3020	1	1	0	1
NORTH ZEPHYR CREEK	3030	1	1	0	1
LINCOLN CREEK	3040	3	2	0	2
CAVE ROCK	3050	1	0	0	0
LOGAN HOUSE CREEK	3060	5	4	0	4
NORTH LOGAN HOUSE CREEK	3070	2	1	0	1
GLENBROOK CREEK	3080	32	26	22	47
BIJOU CREEK	4010	85	71	0	71
EDGEWOOD CREEK	4020	26	22	5	27
BURKE CREEK	4030	7	6	0	6
UPPER TRUCKEE RIVER	5010	2219	1309	2259	3569
TROUT CREEK	5050	257	205	3	208
GENERAL CREEK	6010	160	59	48	107
MEEKS	6020	137	54	12	66
SIERRA CREEK	6030	35	23	0	23
LONELY GULCH CREEK	6040	36	25	0	25
PARADISE FLAT	6050	11	7	0	7
RUBICON CREEK	6060	90	59	3	62
EAGLE CREEK	6080	40	22	0	22
CASCADE CREEK	6090	20	13	0	13
TALLAC CREEK	6100	52	31	0	32
TAYLOR CREEK	6110	272	137	3	139
UNNAMED CK	6120	16	11	0	11
BLACKWOOD CREEK	7010	1816	839	873	1712
MADDEN CREEK	7020	918	268	0	269
HOMEWOOD CREEK	7030	908	272	0	272
QUAIL LAKE CREEK	7040	405	123	0	123
MKINNEY CREEK	7050	192	88	0	88
DOLLAR CREEK	8010	113	51	1	51
UNNAMED CK LAKE FOREST 1	8020	92	65	0	65
UNNAMED CK LAKE FOREST 2	8030	92	47	0	47
BURTON CREEK	8040	366	117	1	118
TAHOE STATE PARK	8050	57	32	0	32
WARD CREEK	8060	2994	1439	485	1924
KINGS BEACH	9010	57	29	0	29

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
GRIFF CREEK	9020	300	114	5	119
TAHOE VISTA	9030	489	223	2	225
CARNELIAN CANYON	9040	168	70	0	70
CARNELIAN BAY CREEK	9050	39	14	0	14
WATSON	9060	119	39	0	39
TOTAL		13979	6898	3768	10670
GRAND TOTAL		16921	9100	3768	12872
CONTRIBUTION FROM IZ		17%	24%	0%	17%
CONTRIBUTION FROM STREAMS		83%	76%	100%	83%

Table 4-33. Summary of annual upland TSS loads, upland fines loads and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using the Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Upland TSS (metric tons/year)	Upland Fines (metric tons/year)	Upland TSS Concentration (mg/L)	Upland Fines Concentration (mg/L)
U	Residential_SFP	269	205	103	78
U	Residential_MFP	194	172	418	370
U	CICU-Pervious	205	175	555	474
U	Residential_SFI	319	243	56	42
U	Residential_MFI	358	316	160	141
U	CICU-Impervious	788	673	260	222
U	Roads_Primary	1,720	1,470	950	811
U	Roads_Secondary	1,380	1,180	154	131
NU	Ski_Runs-Pervious	695	227	848	278
NU	Veg_EP1	20.9	8.93	6	3
NU	Veg_EP2	3,050	290	26	11
NU	Veg_EP3	3,050	1,230	163	66
NU	Veg_EP4	5,810	2,360	957	388

Urban/Non-urban Category	Land-use	Upland TSS (metric tons/year)	Upland Fines (metric tons/year)	Upland TSS Concentration (mg/L)	Upland Fines Concentration (mg/L)
NU	Veg_ep5	686	288	2640	1110
NU	Veg_Recreational	41.3	17.2	326	135
NU	Veg_Burned	189	68.7	941	342
NU	Veg_Harvest	142	54.1	1520	577
NU	Veg_Turf	7.49	2.72	34	12
NU	Roads_Unpaved	354	126	2150	770
U	**TOTAL LOAD**	**5233**	**4434**		
NU	**TOTAL LOAD**	**11687**	**4673**		
	GRAND TOTAL	16920	9107		
	CONTRIBUTION FROM URBAN	31%	49%		
	CONTRIBUTION FROM NON-URBAN	69%	51%		

An examination of upland TSS and upland fine sediment loading by specific land-use category is presented in Table 4-31, Table 4-33 and Figure 4-32. The largest contributors in decreasing order were vegetated-erosion potential-4, vegetated-erosion potential-3, primary roads, secondary road, CICU commercial, and ski runs. These contributed nearly 80 percent of the upland TSS load. Single and multiple family residential contributed 7 percent of the total upland TSS load. Within the urban category, primary and secondary roads plus CICU commercial accounted for about 75 percent of the upland TSS load.

For upland fine sediment (< 63 μm), the top six contributors in descending order were vegetated-erosion potential-4, primary roads, vegetated-erosion potential-3, secondary roads, CICU commercial and single family residences. These accounted for > 80 percent of the total 9,107 metric tons/year load from upland fines. Estimated concentrations for upland TSS and upland fines are also given in Table 4-33.

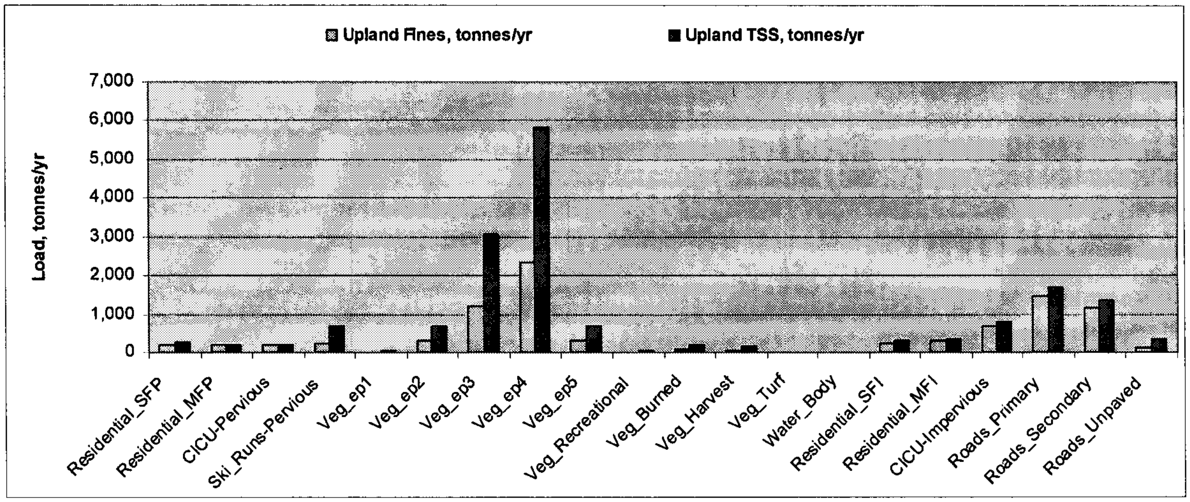

Figure 4-32. Upland TSS and upland fine sediment loading by land-use category as determined by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (note: tonnes is referred to as metric tons in this report) (Tetra Tech 2007).

The loads in Figure 4-32, Table 4-31, and Table 4-32 are dependent upon flow volume, concentration and area. Figure 4-33 provides an example of the relative load for upland TSS when expressed on a per unit area basis. As can be seen a very large amount of TSS comes from each hectare of primary road surface with minimal values for turf, vegetated and single family residential land-uses. It is important to keep in mind that a unit area load may be high but if the total area of that land-use is small; its contribution to basin-wide loading is likely to be low. Figure 4-34 and Figure 4-35 show modeling results for unit-area TSS and fine sediment around the basin.

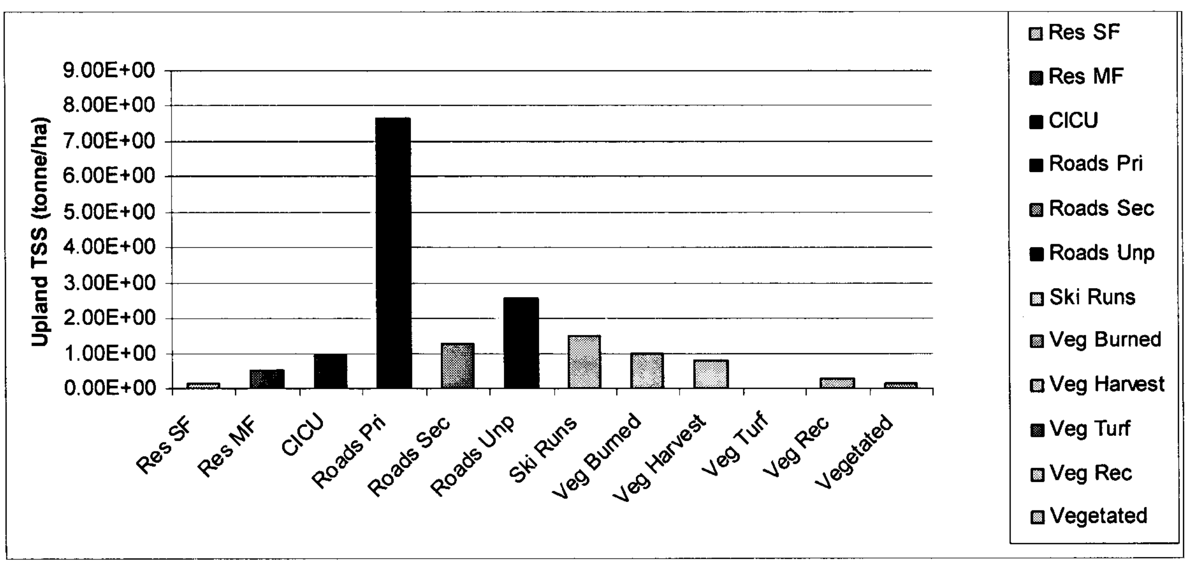

Figure 4-33. Relative upland TSS load from selected land-use categories as compared on a per unit area (per hectare) basis (note: tonne is referred to as metric ton in this report) (Tetra Tech 2007).

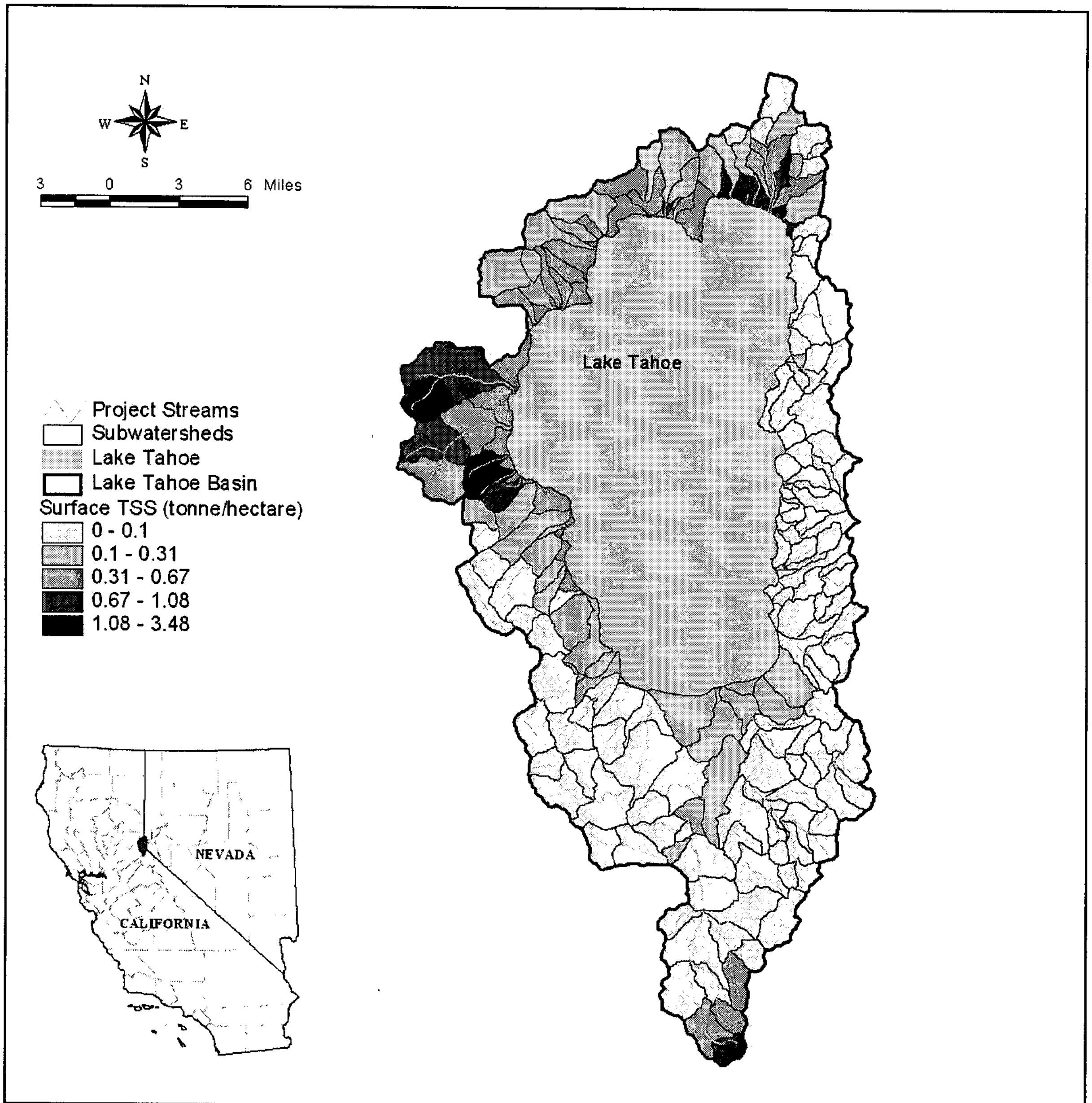

Figure 4-34. Unit-area annual total sediment yield (metric tons/ha) by subwatershed (note: tonnes is referred to as metric tons in this report) (Tetra Tech 2007).

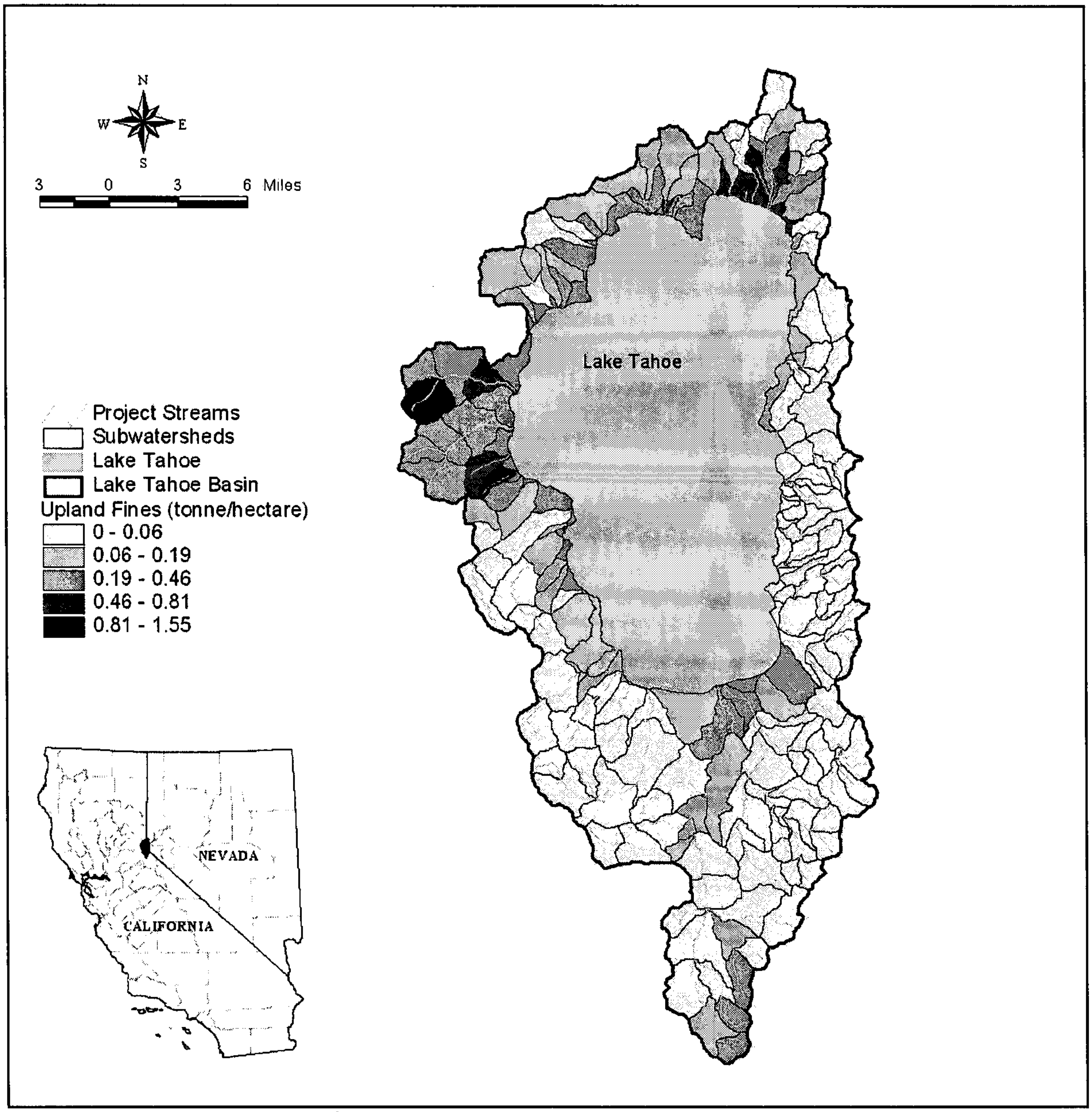

Figure 4-35. Unit-area annual fine sediment yield (metric tons/ha) by subwatershed (note: tonne is referred to as metric ton in this report) (Tetra Tech 2007).

Nitrogen

The load of total nitrogen (TN) from watershed sources was estimated by the Tahoe Watershed Model to be approximately 125 metric tons/year over the 1994-2004 calibration period (Table 4-34) (note: that in this discussion all values refer to just the nitrogen content of the compounds; i.e. expressed in units of nitrogen). This agrees well with the value of 105 metric tons for TN reported using data collected prior 1993 (Reuter et al. 2003). The latter estimate was not based on modeling, but rather on extrapolation of the LTIMP or other even more limited databases to the whole basin.

Given the different time periods for each estimate and the fact that the applied methods of calculation were so different, the similarity of results is noteworthy.

Of the 125 metric tons total load, 25 percent was estimated to come from intervening zones and 75 percent from stream flow (Table 4-34). Again, using different and less sophisticated methodologies the reported contributions from stream flow and intervening zones were nearly identical at 78 percent and 22 percent, respectively Reuter et al. (2003). As expected based on flow, the Upper Truckee River was the largest single contributor with a load of about 24 metric tons/year or 25 percent of all streams.

Table 4-34. Summary of annual surface, base and total nitrogen by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface TN Load (kg)	Baseflow TN Load (kg)	Total TN Load (kg)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	2631	280	2911
IVZ2000	2000	502	582	1084
IVZ3000	3000	1039	229	1268
IVZ4000	4000	4062	192	4254
IVZ5000	5000	2484	316	2800
IVZ6000	6000	870	929	1799
IVZ6001	6001	1990	232	2221
IVZ7000	7000	4390	462	4852
IVZ8000	8000	5588	514	6102
IVZ9000	9000	3196	823	4019
TOTAL		26752	4559	31310
STREAM FLOW				
MILL CREEK	1010	593	341	934
INCLINE CREEK	1020	2173	1127	3300
THIRD CREEK	1030	1846	978	2824
WOOD CREEK	1040	651	311	962
BURNT CEDAR CREEK	1050	465	38	502
SECOND CREEK	1060	230	220	450
FIRST CREEK	1070	118	285	403
SLAUGHTER HOUSE	2010	140	249	389
BLISS CREEK	2020	33	69	102
SECRET HARBOR CREEK	2030	108	438	546
MARLETTE CREEK	2040	132	541	673
BONPLAND	2050	20	109	129
TUNNEL CREEK	2060	23	218	240

MCFAUL CREEK	3010	131	217	349
ZEPHYR CREEK	3020	52	98	150
NORTH ZEPHYR CREEK	3030	33	156	189
LINCOLN CREEK	3040	31	147	179
CAVE ROCK	3050	20	43	63
LOGAN HOUSE CREEK	3060	34	124	157
NORTH LOGAN HOUSE CREEK	3070	12	56	69
GLENBROOK CREEK	3080	166	216	383
BIJOU CREEK	4010	1455	126	1581
EDGEWOOD CREEK	4020	1154	217	1371
BURKE CREEK	4030	350	189	539
UPPER TRUCKEE RIVER	5010	13981	10133	24115
TROUT CREEK	5050	4046	2492	6538
GENERAL CREEK	6010	1201	1944	3145
MEEKS	6020	1376	2084	3460
SIERRA CREEK	6030	380	221	601
LONELY GULCH CREEK	6040	578	273	851
PARADISE FLAT	6050	175	159	334
RUBICON CREEK	6060	982	725	1707
EAGLE CREEK	6080	444	2479	2923
CASCADE CREEK	6090	213	853	1067
TALLAC CREEK	6100	291	421	712
TAYLOR CREEK	6110	1872	3512	5384
UNNAMED CK	6120	188	65	254
BLACKWOOD CREEK	7010	1850	6553	8402
MADDEN CREEK	7020	419	533	952
HOMEWOOD CREEK	7030	360	260	619
QUAIL LAKE CREEK	7040	364	371	735
MKINNEY CREEK	7050	1949	1177	3126
DOLLAR CREEK	8010	111	166	277
UNNAMED CK LAKE FOREST 1	8020	487	97	584
UNNAMED CK LAKE FOREST 2	8030	196	152	348
BURTON CREEK	8040	61	805	866
TAHOE STATE PARK	8050	108	160	268
WARD CREEK	8060	2883	3561	6444
KINGS BEACH	9010	191	62	254
GRIFF CREEK	9020	308	669	978
TAHOE VISTA	9030	1078	695	1773
CARNELIAN CANYON	9040	267	463	730
CARNELIAN BAY CREEK	9050	28	135	164
WATSON	9060	66	350	416
TOTAL		46423	48083	94511
GRAND TOTAL		73175	52646	125821
CONTRIBUTION FROM IZ		37%	9%	25%
CONTRIBUTION FROM STREAMS		63%	91%	75%

The contribution of dissolved inorganic-N (nitrate + ammonium; and those forms most readily used by algae) is presented in Table 4-35. Combined annual DIN loading from streams flow and intervening zones was modeled at 11.8 metric tons/year over the 1994-2004 calibration period. The ratio of DIN to TN was 9 percent, with organic-N accounting for the vast majority of TN. This finding from the Tahoe Watershed Model was identical to the finding in Coats and Goldman (2001) that for Lake Tahoe streams the discharge weighted concentration of organic-N was usually 10 times that of inorganic-N. Model results suggested that TN load from the intervening zones were 31 percent of the total combined load with 69 percent contributed from stream flow (Table 4-35). As for the other pollutants considered in this study, the contribution of the intervening zones was approximately 2 – 3 times that of flow. This highlights the fact that many of the urban areas – with elevated pollutant concentrations – are located in the intervening zones. Finally, while baseflow and surface TN loads were nearly the same for the stream flow sources, surface TN load exceed baseflow TN load in the intervening zones by factor of nearly 6-fold.

Table 4-35. Summary of annual loads for dissolved inorganic-N (sum of nitrate and ammonium) and soluble reactive-P by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (Tetra Tech unpublished).

Tributary	Soluble Reactive-P (kg)	DIN (kg)
INTERVENING ZONE RUNOFF		
IVZ1000	129	356
IVZ2000	51	90
IVZ3000	59	140
IVZ4000	89	552
IVZ5000	70	340
IVZ6000	100	159
IVZ6001	89	245
IVZ7000	251	561
IVZ8000	395	761
IVZ9000	189	463
TOTAL	1423	3667
STREAM FLOW		
MILL CREEK	45	91
INCLINE CREEK	172	338
THIRD CREEK	173	2844
WOOD CREEK	46	102
BURNT CEDAR CREEK	20	63
SECOND CREEK	23	42
FIRST CREEK	26	30
SLAUGHTER HOUSE	44	30
BLISS CREEK	5	8
SECRET HARBOR CREEK	26	36
MARLETTE CREEK	32	44

Tributary	Soluble Reactive-P (kg)	DIN (kg)
BONPLAND	6	8
TUNNEL CREEK	15	14
MCFAUL CREEK	14	26
ZEPHYR CREEK	6	11
NORTH ZEPHYR CREEK	9	12
LINCOLN CREEK	9	11
CAVE ROCK	3	5
LOGAN HOUSE CREEK	8	10
NORTH LOGAN HOUSE CREEK	10	4
GLENBROOK CREEK	42	31
BIJOU CREEK	34	199
EDGEWOOD CREEK	41	160
BURKE CREEK	14	56
UPPER TRUCKEE RIVER	833	2283
TROUT CREEK	183	663
GENERAL CREEK	129	221
MEEKS	140	241
SIERRA CREEK	25	54
LONELY GULCH CREEK	32	82
PARADISE FLAT	13	26
RUBICON CREEK	73	140
EAGLE CREEK	146	180
CASCADE CREEK	47	69
TALLAC CREEK	30	57
TAYLOR CREEK	227	389
UNNAMED CK	10	26
BLACKWOOD CREEK	668	573
MADDEN CREEK	91	66
HOMEWOOD CREEK	87	50
QUAIL LAKE CREEK	48	58
MKINNEY CREEK	117	283
DOLLAR CREEK	22	23
UNNAMED CK LAKE FOREST 1	26	69
UNNAMED CK LAKE FOREST 2	21	33
BURTON CREEK	69	52
TAHOE STATE PARK	19	23
WARD CREEK	456	508
KINGS BEACH	11	29
GRIFF CREEK	70	76
TAHOE VISTA	133	174
CARNELIAN CANYON	52	59
CARNELIAN BAY CREEK	13	11

Tributary	Soluble Reactive-P (kg)	DIN (kg)
WATSON	31	28
TOTAL	4646	8158
GRAND TOTAL	6069	11825
CONTRIBUTION FROM IZ	23%	31%
CONTRIBUTION FROM STREAMS	72%	69%

The previous observation regarding elevated nitrogen concentrations in urban areas is supported by the nitrogen load estimates separated on the basis of urban versus non-urban land-use (Table 4-36). Despite the finding that urban zones only contributed 10 percent of the total flow volume (Table 4-30), the TN loads from urban and non-urban land-use areas were identical with each representing 50 percent of the total load. Notice the much higher TN concentrations for surface flow coming from urban land-uses (Table 4-36). Baseflow concentrations were relatively uniform because much of the organic load could be trapped as the flow infiltrated into and through the natural soils.

Table 4-36. Summary of annual upland surface, base, and total nitrogen loads, and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using the Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface TN (kg/year)	Baseflow TN (kg/year)	Total TN (kg/year)	Surface TN Concentration (mg/L)	Baseflow TN Concentration (mg/L)
U	Residential_SFP	4,920	1,980	6,900	1.88	0.14
U	Residential_MFP	1,310	484	1,790	2.81	0.14
U	CICU-Pervious	891	373	1,260	2.41	0.14
U	Residential_SFI	9,440	0	9,440	1.64	NA
U	Residential_MFI	5,860	0	5,860	2.62	NA
U	CICU-Impervious	6,380	0	6,380	2.10	NA
U	Roads_Primary	6,740	0	6,740	3.72	NA
U	Roads_Secondary	25,100	0	25,100	2.79	NA

Urban/Non-urban Category	Land-use	Surface TN (kg/year)	Baseflow TN (kg/year)	Total TN (kg/year)	Surface TN Concentration (mg/L)	Baseflow TN Concentration (mg/L)
NU	Ski_Runs-Pervious	415	352	767	0.51	.0.15
NU	Veg_EP1	459	2,530	2,990	0.14	0.13
NU	Veg_EP2	4,430	22,100	26,500	0.17	0.14
NU	Veg_EP3	3,840	17,000	20,800	0.21	0.17
NU	Veg_EP4	1,300	6,910	8,210	0.21	0.18
NU	Veg_eEP5	64.9	246	311	0.25	0.20
NU	Veg_Recreational	153	89.1	242	1.21	0.15
NU	Veg_Burned	431	110	541	2.14	0.13
NU	Veg_Harvest	165	81.7	247	1.76	0.12
NU	Veg_Turf	842	232	1,070	3.85	0.14
NU	Roads_Unpaved	470	106	576	2.86	1.15
U	**TOTAL LOAD**	**60641**	**2837**	**63478**		
NU	**TOTAL LOAD**	**12569**	**49757**	**62326**		
	GRAND TOTAL	73210	52594	125804		
	CONTRIBUTION FROM URBAN	83%	55%	50%		
	CONTRIBUTION FROM NON-URBAN	17%	95%	50%		

The TN loading data contained in Table 4-35 are plotted in Figure 4-36 and is summarized in Table 4-31. It was estimated that 50 percent of the TN coming from urban land-uses came from primary (approximately 10 percent) and secondary (approximately 40 percent) roads; or 26 percent from all land-uses. Single and multiple family residences combined 38 percent of the TN load from urban areas and 20 percent from all land-uses. More than 95 percent of the TN load from non-urban areas came from the vegetated forest (EP1-EP5); this source was 46 percent of the total watershed TN load.

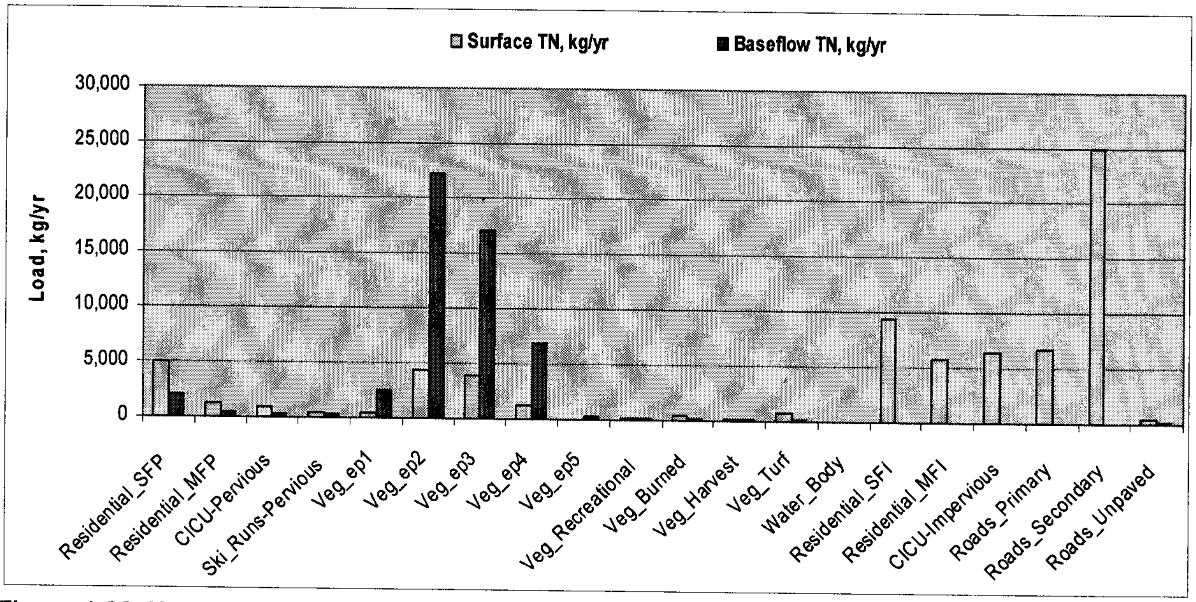

Figure 4-36. Upland total nitrogen loading by land-use category as determine by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (Tetra Tech 2007).

Figure 4-37 demonstrates that as found for TSS, the primary roads deliver the most TN per unit area, followed closely by secondary roads. Again, it is important to note that while the per unit TN load from the vegetated forest is the lowest, when the extent of forested land area and runoff is considered, it becomes the most significant contributor. Figure 4-38 shows the distribution of unit-area loading for TN around the basin.

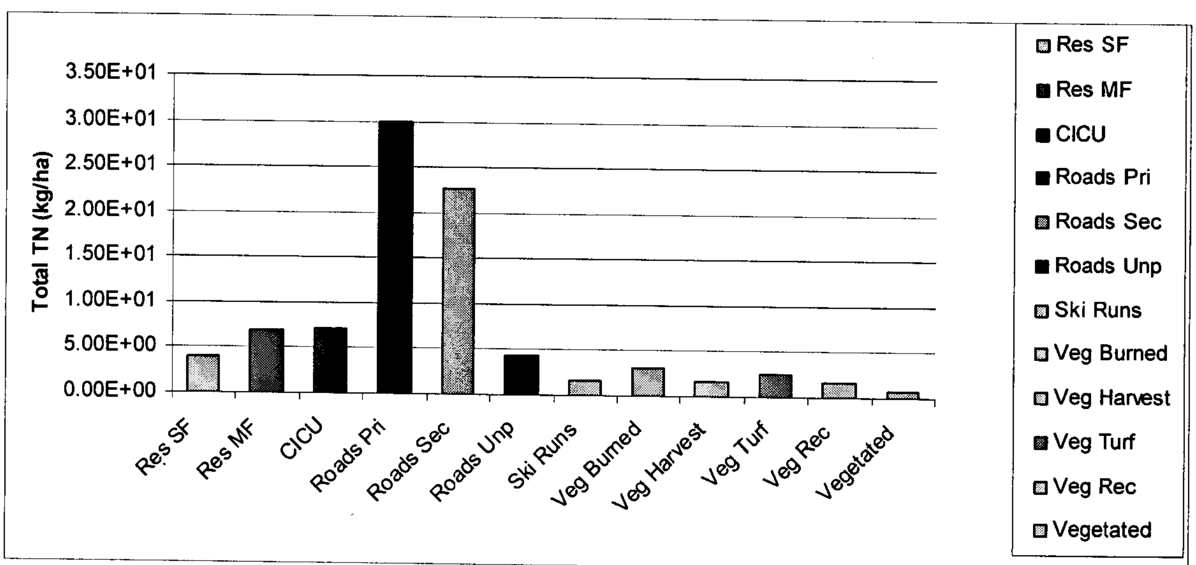

Figure 4-37. Relative upland nitrogen load from selected land-use categories as compared on a per unit area (per hectare) basis (Tetra Tech 2007).

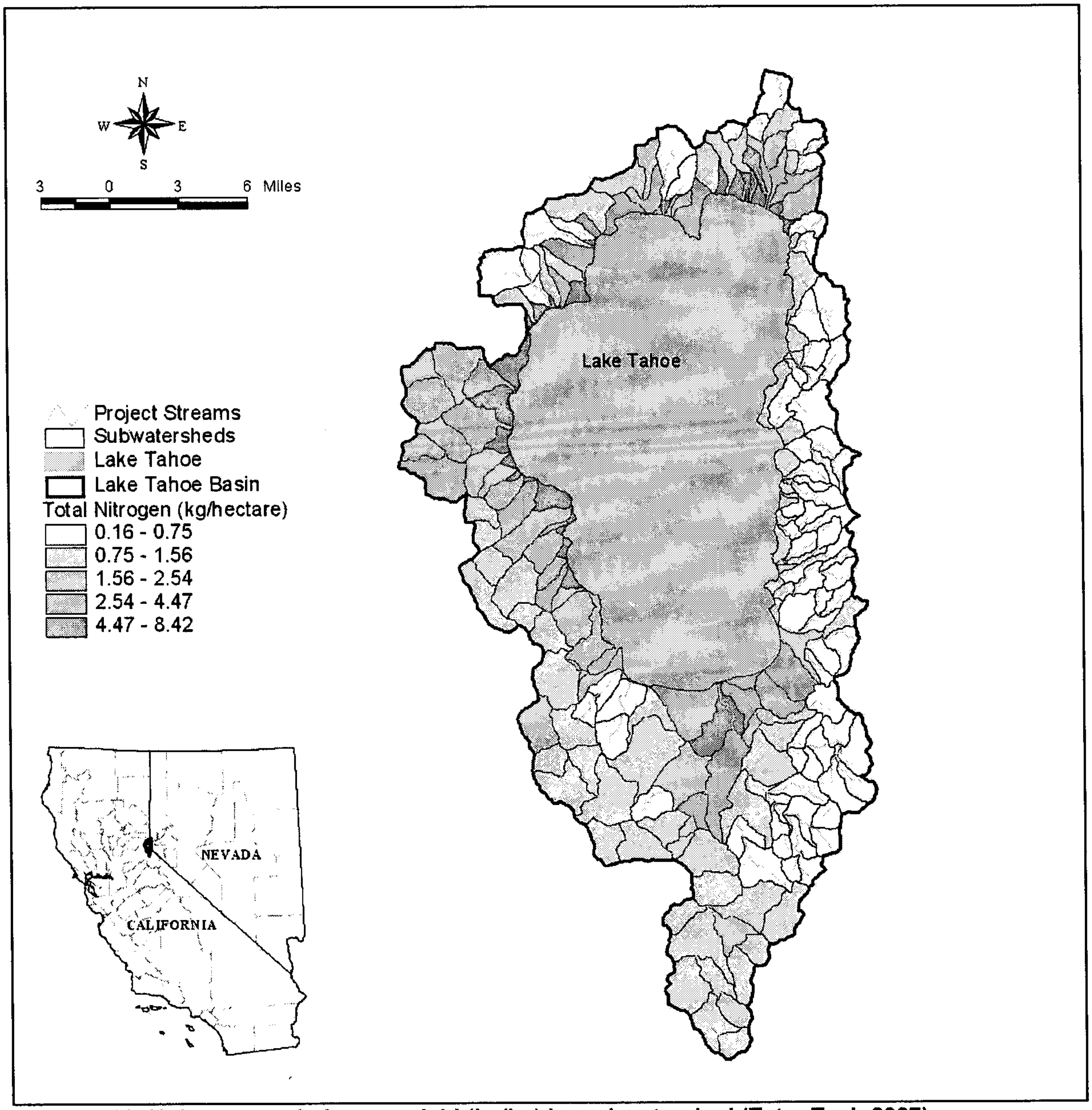

Figure 4-38. Unit-area total nitrogen yield (kg/ha) by subwatershed (Tetra Tech 2007).

An analysis of DIN loading by land-use is summarized in Table 4-37. Average annual loading attributed to urban land-uses was approximately 8 metric tons compared to 3.9 metric tons for the non-urban land-uses. The 2:1 ratio of DIN load from urban versus no-urban was higher than the 1:1 ratio seen for TN loading from these two land-use categories, respectively. This identifies the urban areas as an important source of DIN. Within the urban land area, secondary (43 percent) and primary roads (11 percent) accounted for greater than half the urban DIN load with single and multiple family residental accounting for 34 percent of the urban DIN load. Commercial/industrial land-use contributed about 12 percent.

Of the 3.9 metric tons/year for DIN estimated to come from non-urban land-uses, 90-95 percent was attributed to the vegetated, undeveloped regions (EP1-EP5). Negligible amounts of DIN appeared to results from the remaining land-uses within the non-urban classification (e.g. veg-recreational, veg-turf, burned, harvested, ski runs).

Table 4-37. Summary of annual upland dissolved inorganic-N (nitrate+ammonium) and soluble reactive-P loads, and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (Tetra Tech unpublished).

Urban/Non-Urban	Land-use	Soluble Reactive-P (kg/yr)	DIN (kg/yr)	Soluble Reactive-P Concentration (mg/L)	DIN Concentration (mg/L)
U	Residential_SFP	515	512	0.0304	0.0302
U	Residential_MFP	147	133	0.0383	0.0348
U	CICU-Pervious	100	93	0.0320	0.0298
U	Residential_SFI	272	1275	0.0475	0.2220
U	Residential_MFI	126	791	0.0562	0.3533
U	CICU-Impervious	171	862	0.0563	0.2841
U	Roads_Primary	396	910	0.2185	0.5023
U	Roads_Secondary	588	3386	0.0655	0.3774
NU	Ski_Runs-Pervious	93	54	0.0288	0.0166
NU	Veg_EP1	138	182	0.0058	0.0077
NU	Veg_EP2	1328	1624	0.0072	0.0088
NU	Veg_EP3	1205	1281	0.0100	0.0106
NU	Veg_EP4	595	500	0.0135	0.0114
NU	Veg_EP5	32	19	0.0213	0.0128
NU	Veg_Recreational	23	17	0.0311	0.0238
NU	Veg_Burned	54	41	0.0510	0.0388
NU	Veg_Harvest	31	18	0.0410	0.0238
NU	Veg_Turf	123	81	0.0637	0.0420
U	**TOTAL LOAD**	2320	7960		
NU	**TOTAL LOAD**	3750	3860		
	GRAND TOTAL	6070	11820		
	CONTRIBUTION FROM URBAN	38%	67%		
	CONTRIBUTION FROM NON-URBAN	62%	33%		

Phosphorus

The load of total phosphorus (TP) from watershed sources was estimated by the Tahoe Watershed Model to be approximately 30 metric tons/year over the 1994-2004 calibration period (Table 4-38). Again, this agrees well with the overall value of 26 metric tons for TP reported using data collected prior to 1993 (Reuter et al. 2003). As noted above for TN, the latter estimate was not based on modeling, but rather on extrapolation of the LTIMP data to the whole basin. Given the different time periods for each estimate and the fact that the applied methods of calculation were so different, the results are nonetheless very similar.

Of the 30 metric tons total load for TP, 32 percent was estimated to come from intervening zones with 68 percent from stream flow (Table 4-38). This differs from Reuter et al. (2003) who reported an equal contribution from each source. In fact, it was the identified uncertainty associated with the intervening zones loads (Reuter and Miller 2000, Reuter et al. 2003) that prompted more detailed studies to be undertaken as part of the TMDL effort. The Upper Truckee River was the largest single contributor with a load of about 4 metric tons/year or 20 percent of all streams. Combined, the Upper Truckee River and Trout Creek contributed just over 5 metric tons/year, while the west shore tributaries of Ward Creek and Blackwood Creek were not far behind with a combined load of > 4 metric tons/year.

The modeled combined load for ortho-P and SRP from both streams and the intervening zone sources was 6 metric tons/year with 23 percent from intervening zones and the remaining 72 percent from upland stream flow (Table 4-35). For the purposes of this document, ortho-phosphorus and SRP are indistinguishable, as they are both considered immediately available for algal growth. The calculated ratios of SRP:TP were 20 percent for all sources, 15 percent for intervening zones and 23 percent for stream flow. The 20 percent value for SRP:TP was higher than the approximately 10 percent value for DIN/TN. While Tahoe-specific studies have not been done, it is likely that this is related to the fact that SRP can be readily leached into water from particulate-phosphorus associated with sediment.

Table 4-38. Summary of annual surface, base and total phosphorus by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	772	60	831
IVZ2000	2000	180	82	263

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
IVZ3000	3000	169	102	270
IVZ4000	4000	739	21	760
IVZ5000	5000	477	42	519
IVZ6000	6000	439	135	574
IVZ6001	6001	639	26	665
IVZ7000	7000	1717	53	1770
IVZ8000	8000	2858	92	2950
IVZ9000	9000	951	176	1127
TOTAL		8941	789	9729
STREAM FLOW				
MILL CREEK	1010	159	66	224
INCLINE CREEK	1020	657	221	877
THIRD CREEK	1030	632	211	843
WOOD CREEK	1040	166	67	232
BURNT CEDAR CREEK	1050	131	8	139
SECOND CREEK	1060	49	47	96
FIRST CREEK	1070	29	61	90
SLAUGHTER HOUSE	2010	31	110	141
BLISS CREEK	2020	14	10	23
SECRET HARBOR CREEK	2030	29	62	91
MARLETTE CREEK	2040	33	76	109
BONPLAND	2050	3	15	18
TUNNEL CREEK	2060	4	42	45
MCFAUL CREEK	3010	22	30	52
ZEPHYR CREEK	3020	9	14	23
NORTH ZEPHYR CREEK	3030	7	21	29
LINCOLN CREEK	3040	8	20	28
CAVE ROCK	3050	4	6	9
LOGAN HOUSE CREEK	3060	9	17	26
NORTH LOGAN HOUSE CREEK	3070	4	25	29
GLENBROOK CREEK	3080	47	96	143
BIJOU CREEK	4010	260	14	273
EDGEWOOD CREEK	4020	134	69	203
BURKE CREEK	4030	43	26	69
UPPER TRUCKEE RIVER	5010	2782	1328	4110
TROUT CREEK	5050	728	272	1000
GENERAL CREEK	6010	302	215	517
MEEKS	6020	324	231	555
SIERRA CREEK	6030	125	24	149
LONELY GULCH CREEK	6040	163	30	193
PARADISE FLAT	6050	45	18	62

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
RUBICON CREEK	6060	311	80	391
EAGLE CREEK	6080	112	356	468
CASCADE CREEK	6090	45	111	156
TALLAC CREEK	6100	69	55	125
TAYLOR CREEK	6110	367	462	829
UNNAMED CK	6120	60	7	67
BLACKWOOD CREEK	7010	821	1503	2324
MADDEN CREEK	7020	351	59	410
HOMEWOOD CREEK	7030	398	29	427
QUAIL LAKE CREEK	7040	183	41	224
MKINNEY CREEK	7050	508	130	638
DOLLAR CREEK	8010	53	36	88
UNNAMED CK LAKE FOREST 1	8020	136	21	157
UNNAMED CK LAKE FOREST 2	8030	65	33	98
BURTON CREEK	8040	34	174	209
TAHOE STATE PARK	8050	41	35	76
WARD CREEK	8060	1443	591	2034
KINGS BEACH	9010	48	13	61
GRIFF CREEK	9020	117	146	263
TAHOE VISTA	9030	489	150	640
CARNELIAN CANYON	9040	99	100	199
CARNELIAN BAY CREEK	9050	14	29	43
WATSON	9060	23	77	100
TOTAL		12740	7690	20425
GRAND TOTAL		21681	8479	30154
CONTRIBUTION FROM IZ		41%	9%	32%
CONTRIBUTION FROM STREAMS		59%	91%	68%

TP load from urban land-uses was modeled at approximately 18 metric tons/year (59 percent) and somewhat higher than the approximately 12 metric tons/year (41 percent) estimated to come from non-urban land-uses (Table 4-31, Table 4-39). Within the urban areas, primary and secondary roads contributed approximately 45 percent of the TP load or 30 percent to the TP load from both intervening zones and upland stream sources. Both single family and multiple family residences combined contributed 35 – 40 percent of the TP from urban land-uses and 22 percent of the TP from both intervening zones and upland stream sources (Figure 4-39). For the non-urban land-uses, the vegetated forest areas contributed 80 – 85 percent of the TP load. This amounted to approximately 35 percent of the total TP load.

The calculated TP based on a unit area approach (Figure 4-40) was very similar to that seen for TSS (Figure 4-33) with primary roads as the largest contributor. This is not surprising given the close relationship between TSS and TP in the Tahoe basin (Hatch 1997, Hatch et al. 2001). Figure 4-41 provides the basin-wide distribution of unit-area TP loading.

Table 4-39. Summary of annual upland surface, baseflow and total phosphorus loads, and associated flow-weighted average concentration by land by use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface TP (kg/year)	Baseflow TP (kg/year)	Total TP (kg/year)	Surface TP Concentration (µg/L)	Baseflow TP Concentration (µg/L)
U	Residential_SFP	1,950	343	2,290	0.75	0.02
U	Residential_MFP	565	92.4	657	1.22	0.03
U	CICU-Pervious	384	63.2	447	1.04	0.02
U	Residential_SFI	2,500	0	2,500	0.44	NA
U	Residential_MFI	1,160	0	1,160	0.52	NA
U	CICU-Impervious	1,570	0	1,570	0.52	NA
U	Roads_Primary	3,640	0	3,640	2.01	NA
U	Roads_Secondary	5,400	0	5,400	0.60	NA
NU	Ski_Runs-Pervious	370	51.3	421	0.45	0.02
NU	Veg_EP1	76.9	344	421	0.02	0.02
NU	Veg_EP2	780	3,290	4,070	0.03	0.02
NU	Veg_EP3	910	2,870	3,780	0.05	0.03
NU	Veg_EP4	700	1,270	1,970	0.12	0.03
NU	Veg_EP5	82.1	43.7	126	0.32	0.04
NU	Veg_Recreational	90.3	13.0	103	0.71	0.02
NU	Veg_Burned	234	19.1	253	1.17	0.02
NU	Veg_Harvest	126	15.9	142	1.34	0.02
NU	Veg_Turf	528	47.1	575	2.41	0.03
NU	Roads_Unpaved	614	17.7	632	3.74	0.03
U	**TOTAL LOAD**	**17169**	**499**	**17688**		
NU	**TOTAL LOAD**	**4511**	**7982**	**12493**		
	GRAND TOTAL	21680	8480	30161		
	FROM URBAN	79%	6%	59%		
	FROM NON-URBAN	21%	94%	41%		

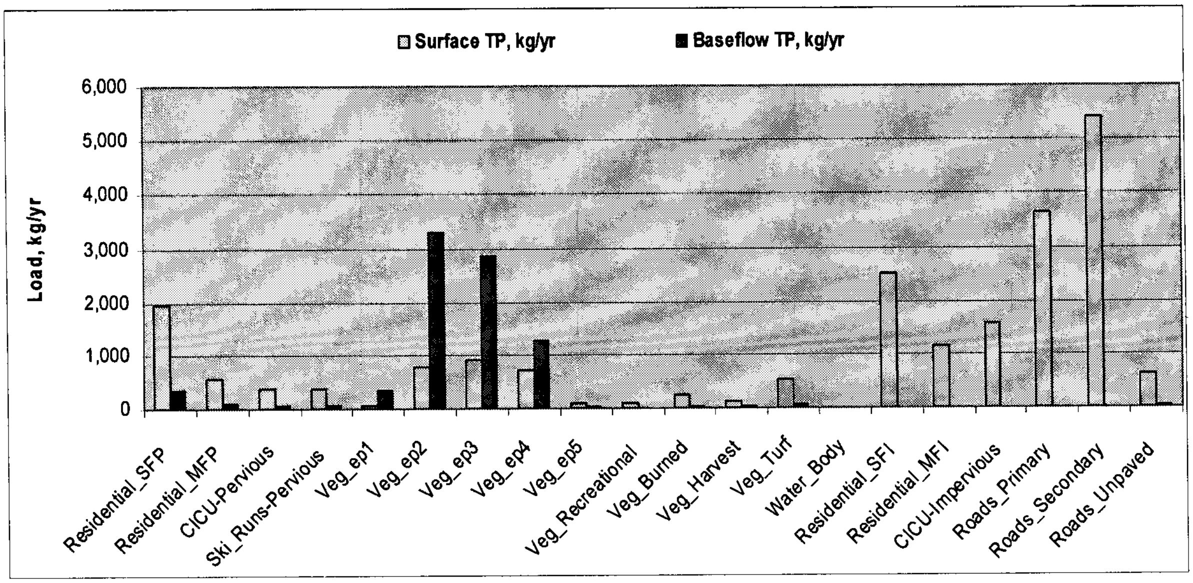

Figure 4-39. Upland total phosphorus loading by land-use category as determine by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (Tetra Tech 2007).

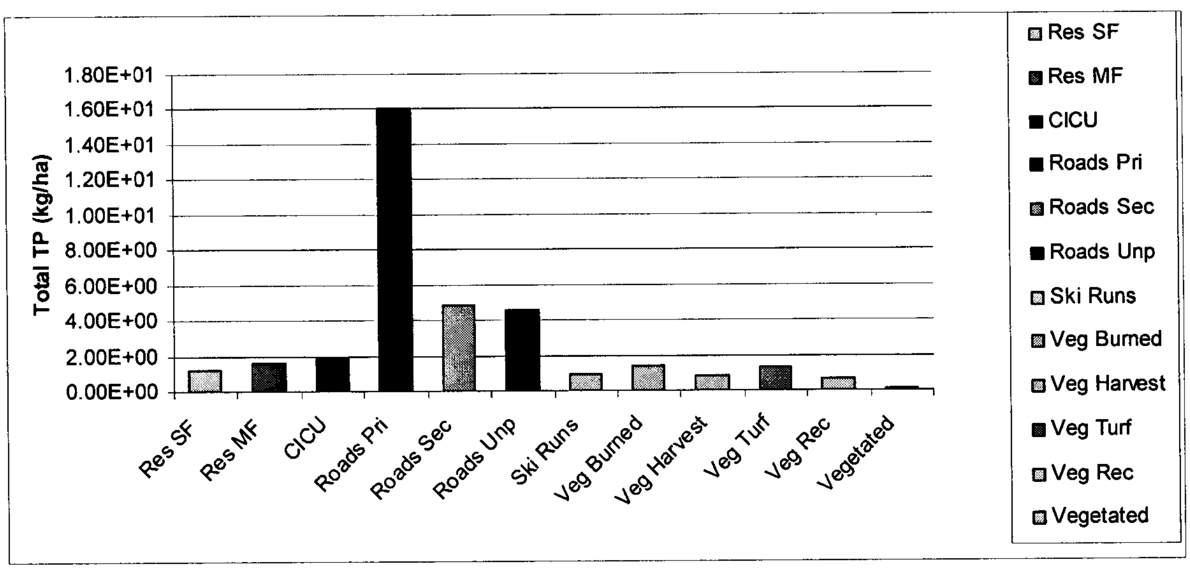

Figure 4-40. Relative upland phosphorus load from selected land-use categories as compared on a per unit area (per hectare) basis (Tetra Tech 2007).

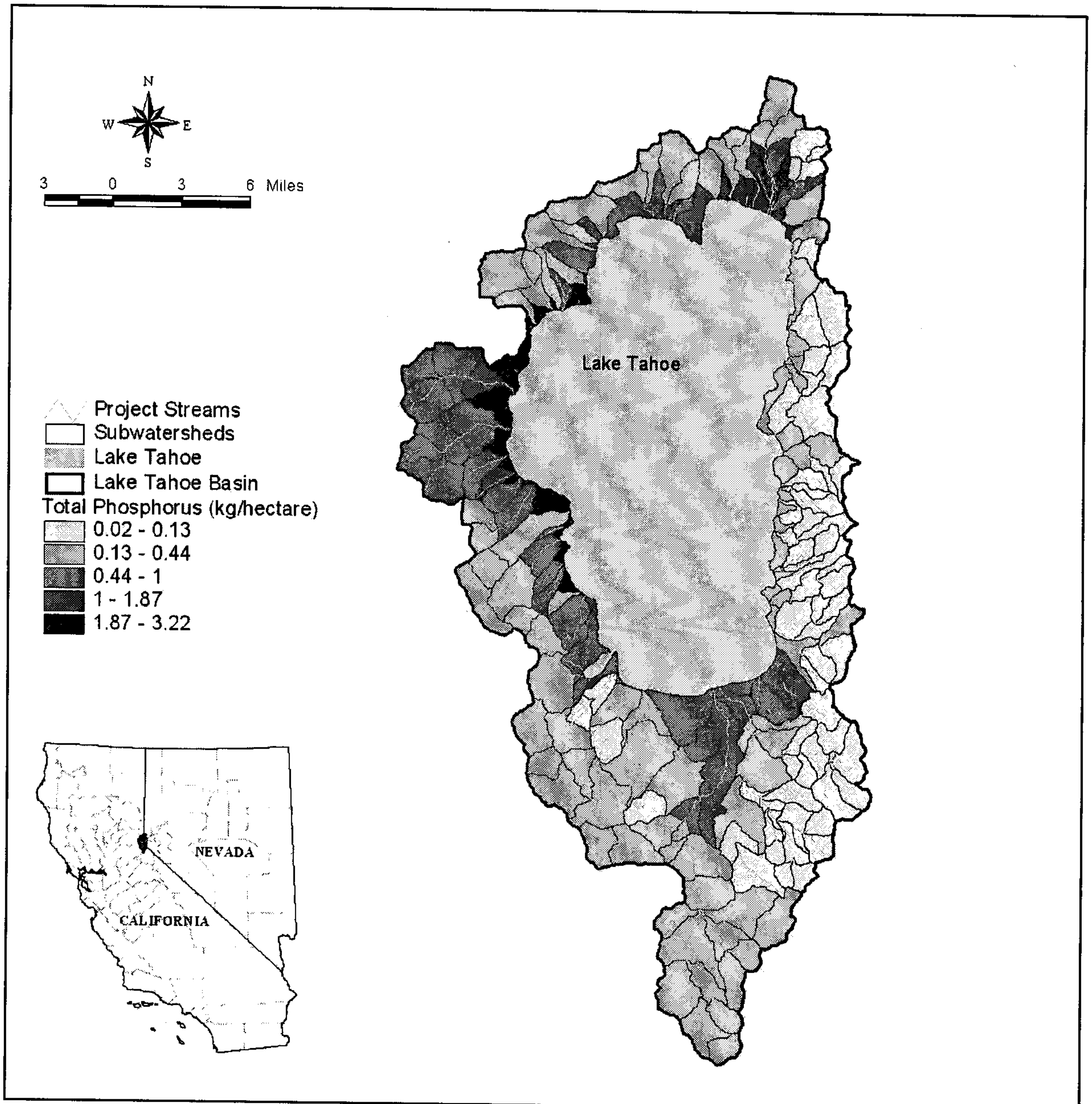

Figure 4-41. Unit-area total phosphorus yield (kg/ha) by subwatershed (Tetra Tech 2007).

An analysis of soluble reactive loading by land-use is summarized in Table 4-37. Average annual loading attributed to urban land-uses was 2.3 metric tons compared to 3.8 metric tons for the non-urban land-uses. The larger contribution of SRP estimated from non-urban land-uses (approximately 60 percent) was the opposite of that found for TP here TP from non-urban sources was approximately 40 percent. Within the urban land area, secondary (25 percent) and primary roads (17 percent) accounted for 40 – 45 percent of the urban SRP load with single and multiple family residential accounting for approximately 45 percent of the urban SRP load. Commercial/industrial land-use contributed about 12 percent. Of the 3.8 metric tons/year for SRP estimated to come from non-urban land-uses, 85 – 90 percent was attributed to the vegetated, undeveloped regions (EP1-EP5) (Table 4-37).

Summary of loads from urban and non-urban land-uses

As discussed above, the urban land-uses were taken as single family and multiple family residential, CICU-Commercial and primary/secondary roads. Both the pervious and impervious parcels within the residential and commercial categories were considered. Non-urban land-use were taken as vegetated (EP1-EP5), unpaved roads, ski runs, and vegetated areas with the following uses, recreational, harvested, prescribed burns, ski runs, turf and unpaved roads. Table 4-40 summarizes the finding presented earlier that while flow volume from the urban areas was relatively low, i.e. 10 percent of the total combined overland flow, the contribution of the urban areas to pollutant load was proportionately much higher. Upland contribution of TSS by urban areas was approximately 30 percent; however, the urban contribution increased for upland fine sediment increased to nearly 50 percent. The same was observed for TN with the urban contribution to total TP load the highest at almost 60 percent. These modeled load not only reflect the higher pollutant concentrations associated with urban land-uses, but also indicates that the non-urban areas contribute roughly half the nutrient and sediment load from the watershed.

Table 4-40. Summary of relative loads from urban (U) versus non-urban (NU) land-use categories as modeled for the Tahoe basin using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Total Flow Volume (m^3)	Upland TSS (Metric tons/yr)	Upland Fines (metric tons/year)	Total Nitrogen (metric tons/year)	Total Phosphorus (metric tons/year)
U	4.58×10^7	5,233	4,434	63.5	17.7
	10%	31%	49%	50%	59%
NU	40.2×10^7	11,687	4,673	62.3	12.5
	90%	69%	51%	50%	41%
Total	44.8×10^7	16,920	9,107	125.8	30.2

Lake Tahoe Watershed Model versus LTIMP loading comparison

As discussed in detail above with regard to model development, the Lake Tahoe Watershed Model was calibrated based on 11 years (1994-2004) of field data collected as part of the Lake Tahoe Interagency Monitoring Program (LTIMP). The LTIMP collects on the order of 30 – 40 depth-integrated samples across the width of each stream station each year. These field samples are analyzed for nitrogen, phosphorus and suspended sediment. Annual loads are calculated based on the continuous flow hydrographs recorded at each site (Rowe et al 2002). Table 4-41 presents a comparison between mean annual loads as calculated by the LTIMP program and the Lake Tahoe Watershed Model (LSPC) output for nitrogen, phosphorus and TSS over the 11-year calibration period. The standard deviations presented along with the LTIMP data provides a sense of interannual variability, primarily related to annual precipitation.

While there is some difference between the LTIMP and Lake Tahoe Watershed Model (LSPC) values for certain tributaries and for certain nutrient species (e.g. Blackwood Creek DIN, Ward Creek SRP), there was very good agreement, especially when considering the combined sum for the 10 tributaries (Table 4-41). The relative percent difference (=[LSPC-LTIMP)/mean of LSPC and LTIMP]) was between 10 – 14 percent with the exception of SRP which was much higher at 60 percent. The difference between LTIMP field data and LSPC modeled output for SRP was greatest for the Upper Truckee River, Ward Creek and Blackwood Creeks. While these differences require further investigation, the Lake Clarity Model considers biologically available phosphorus which is derived from both SRP and a fraction of TP. Assuming all SRP is bioavailable and that approximately 20 percent of the remaining phosphorus is bioavailable (Ferguson 2005), an approximation of bioavailable-phosphorus from the10 monitored streams shows the relative percent difference between LTIMP and LSPC reduced to 25 percent.

Table 4-41. Mean annual loading values for the 10 streams monitored as part of LTIMP. Data under the LTIMP label refers to load calculations made by UC Davis-TERC as part of LTIMP reporting. LSPC are modeled results from the Lake Tahoe Watershed Model (Tetra Tech 2007). Mean ± standard deviations refer to model calibration/validation period of 1994-2004. Standard deviations reflect interannual variability with differences in precipitation and flow.

LTIMP Tributaries	DIN (kg) LTIMP	DIN (kg) LSPC	TN (kg) LTIMP	TN (kg) LSPC
Incline Creek	287 ± 164	339	2548 ± 2076	3300
Third Creek	159 ± 132	284	2899 ± 2905	2824
Logan House Creek	13 ± 12	10	184 ± 132	157
Glenbrook Creek	41 ± 28	31	469 ± 328	383
Edgewood Creek	146 ± 93	160	881 ± 392	1371
Upper Truckee River	1818 ± 110	2382	20066 ± 13424	24115
Trout Creek	546 ± 337	663	7638 ± 4853	6538
General Creek	153 ± 88	221	2872 ± 1649	3145
Blackwood Creek	1040 ± 578	573	8500 ± 5501	8402
Ward Creek	450 ± 289	507	5067 ± 3126	6444

Total	4653	5170	51124	56679
PHOSPHORUS (kg)	**SRP** LTIMP	**SRP** LSPC	**TP** LTIMP	**TP** LSPC
Incline Creek	95 ± 61	172	657 ± 516	877
Third Creek	70 ± 44	173	900 ± 1166	843
Logan House Creek	2 ± 2	8	18 ± 15	26
Glenbrook Creek	30 ± 23	42	126 ± 109	143
Edgewood Creek	50 ± 21	42	191 ± 114	203
Upper Truckee River	492 ± 358	833	4037 ± 2898	4110
Trout Creek	307 ± 184	183	1529 ± 1072	1000
General Creek	69 ± 39	89	427 ± 321	517
Blackwood Creek	145 ± 93	667	3417 ± 4172	2324
Ward Creek	164 ± 103	457	2518 ± 3583	2034
Total	1424	2666	13820	12077
TOTAL SUSPENDED SEDIMENT **(metric tons)**		LTIMP	LSPC	
Incline Creek		410 ± 483	419	
Third Creek		967 ± 1733	819	
Logan House Creek		11 ± 22	10	
Glenbrook Creek		36 ± 33	40	
Edgewood Creek		44 ± 32	40	
Upper Truckee River		3189 ± 2572	5091	
Trout Creek		806 ± 836	422	
General Creek		774 ± 1610	388	
Blackwood Creek		4325 ± 6335	5127	
Ward Creek		2952 ± 5009	3166	
Total		13514	15531	

4.4 Stream Channel Erosion

Streams transport water, sediment and pollutants from their drainage basins to the ocean. When watersheds are left undisturbed, in-stream processes reflect a balance that has developed over millennia and function within a state of dynamic equilibrium. However, this balance can be disturbed by changes to flow and/or sediment transport. When these changes occur they manifest themselves most obviously as increased stream channel erosion (Figure 4-42).

Figure 4-42. Photograph of stream channel erosion along the Upper Truckee River.

Traditional development activities (e.g. increasing impervious and disturbed areas) cause increases in the flow and sediment a stream must transport, thereby exacerbating the natural rates of stream channel erosion. Soon after disturbances within a watershed occur, streams will begin to adjust their pattern, profile and cross section. Simon and Hupp (1986) describe this as a process of "stream channel evolution" which can be illustrated by six stages of channel evolution (Figure 4-43). Stage I represents a pre-disturbance condition with Stage VI representing the establishment of a new quasi-equilibrium achieved once conditions have been modified to accommodate the energy shift. Stages III-V are of specific interest to managers in the Lake Tahoe basin, as these stages represent channel instabilities, and mass failures of streambanks (Simon et al. 2003).

Stream systems influenced by watershed disturbance typically illustrate greater instability as a result of shifts in the stream system energy balance. Examples of these disturbances in the Tahoe basin include: changes in hydrologic and sediment contributions from urbanization, direct stream channel modifications and stream channel constrictions. Stream evaluations and modeling completed in the basin by Simon el al. (2003) support these conclusions. Simon et al. (2003) estimated that 79 percent of the annual total suspended sediment load was from the Upper Truckee River, a relatively disturbed stream system, originates from in-channel sources, as compared to 53 percent of the annual total suspended sediment load from General Creek, a relatively undisturbed stream system. Similarly, for fine sediments < 63 µm in diameter, in-channel sources accounted for 51 percent and 28 percent of the load for the Upper Truckee River and General Creek, respectively.

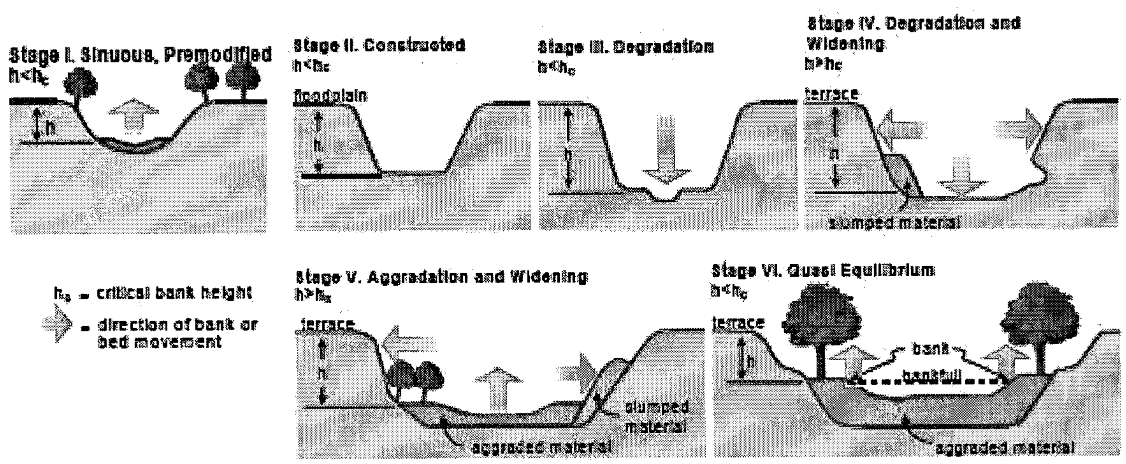

Figure 4-43. Six stages of channel evolution (Simon and Hupp 1986, Simon 1989).

4.4.1 Stream Channel Erosion as a Pollutant Source

Phosphorus and nitrogen are pollutants commonly attached to sediment, which itself is also considered a pollutant. Some of the sediment and nutrients transported by streams is generated from the upland portion of the watershed (described in Section 4.3) and some is generated from stream channel erosion. The distinction between in-channel and upland sources is important for implementation planning, as methods to control pollutants for each are different. This section focuses solely on the pollutant loading from stream channel erosion.

4.4.2 Existing Information

A number of studies have been completed in the past 25 years to address the larger topic of sediment delivery from various watersheds in the Lake Tahoe basin. Many of these studies were focused on individual streams or limited sets of streams, depending on data availability and the scope of the investigation (e.g. Kroll 1976, Glancy 1988, Hill and Nolan 1990, Hill et al. 1990, Stubblefield 2002). Recent analyses by Reuter and Miller (2000) and Rowe et al. (2002) used suspended-sediment transport data from the Lake Tahoe Interagency Monitoring Program (LTIMP), which brought together data from 10 streams all around the basin. These evaluations have indicated that Incline, Third, Blackwood, and Ward Creeks and the Upper Truckee River are the largest contributors of suspended sediment to Lake Tahoe, in ascending order. Although these studies have been valuable for providing quantitative estimates of sediment loading and insight into the spatial and temporal variability of loading, they were not intended to specifically address the relative contribution from in-channel/upland sources. While some early investigations suggested that stream channel erosion could play an important role as a source to the suspended sediment load in some basin streams (Leonard et al. 1979, Hill and Nolan 1990, Hill et al. 1990), this hypothesis was never fully evaluated.

4.4.3 New Information and Additional TMDL-Related Research

In 2002, the National Sedimentation Laboratory in Oxford, Mississippi initiated a study to evaluate the contribution of sediment from stream channel erosion processes as part of the Lake Tahoe TMDL Program. The report, entitled *Lake Tahoe Basin Framework Study: Sediment Loadings and Channel Erosion* (Simon et al. 2003), was designed to combine detailed geomorphic and numerical modeling investigations of several representative watersheds with reconnaissance level evaluation of approximately 300 sites located around the entire Lake Tahoe basin.

Numerical modeling of upland- and channel-erosion processes was conducted using Annualized Agricultural Non-Point Source Pollutant Version 3.30 (AnnAGNPS) and Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) on three representative watersheds: General and Ward Creeks and the Upper Truckee River. GIS-based analysis of land-use, land cover, soil erodibility, steepness, and geology was used to evaluate upland-erosion potential across the basin. Channel contributions to sediment loading were determined by comparing cross-sectional geometries of channels originally surveyed in either 1983 or 1992, including sites along General, Logan House, Blackwood and Edgewood Creeks and the Upper Truckee River, which were re-surveyed in 2002. Historical flow and sediment-transport data from more than 30 sites were used to determine bulk suspended-sediment loads (in metric tons per year) and yields (in metric tons/yr/km^2 of stream channel) for sites all around the lake. Results were reported for both total suspended sediment and fine-grained suspended sediment (< 63 μm in diameter).

Eighteen index stations, defined as those located in a downstream position with long periods of flow and sediment-transport data, were selected. These stations were used to make comparisons between sediment production and delivery from individual watersheds and between different regions of the lake. Fine-grained sediment transport was determined from historical data obtained from 20 sites based on relations derived from particle-size distributions across the range of measured flows.

To better quantify the contributions of fine sediment from stream channel erosion in all 63 tributary stream systems, the National Sedimentation Laboratory completed additional work contained in *Estimates of Fine Sediment Loading to Lake Tahoe from Channel and Watershed Sources* (Simon 2006). Primarily, this study provides valuable information on the average, annual fine-sediment (< 63μm) loadings in metric tones per year from streambank erosion and the relative contribution of each of the basin's 63 streams. Secondarily, it provides additional estimates of average, annual fine-sediment (< 63μm) loadings and average, annual fine-sediment (< 16 μm) loadings in number of particles per year. A summary of the methods applied in these evaluations is provided in the following sections.

Study Methodology & Data Collection

In support of TMDL development, the magnitude and extent of channel erosion was determined using five methods (Simon et al. 2003, Simon 2006):

(1) Direct comparison of monumented, historical stream channel cross-section surveys on Blackwood, Edgewood, General, and Logan House Creeks and the Upper Truckee River
(2) Identification of unstable reaches contributing fine-grained sediment via bank erosion during reconnaissance surveys of geomorphic conditions along Blackwood, Edgewood, Logan House, Incline, General and Ward Creeks and the Upper Truckee River
(3) Rapid geomorphic assessments (RGAs) at 304 locations across the Lake Tahoe basin
(4) Numerical modeling of General Creek, Ward Creek and the Upper Truckee River
(5) Basin-wide evaluation of stream channel erosion based upon results of the above methods and development of a statistically valid (R^2=0.99) empirical relationship between a bank-stability index (I_B) and the measured/modeled rate of streambank erosion.

A summary of the first four of these methods is provided below. The basin-wide evaluation of stream channel erosion is presented following the first four channel erosion methods.

Comparison of Historical Cross-section Surveys

One of the simplest, yet most powerful, ways of estimating channel erosion is by direct comparison of time-series cross-sections. An example of overlain surveys from the Upper Truckee River is provided in Figure 4-44. To obtain a relatively good degree of accuracy it is best to apply historical cross-sections with available measurements taken in both the horizontal and vertical dimensions. Cross sections on Blackwood, General, Logan House and Edgewood Creeks were monumented and labeled (Hill et al. 1990) by the USGS in 1983 and 1984. Original survey notes were obtained from the USGS and new surveys were conducted at as many of these sites as could be located during the USDA survey in the fall of 2002. Time-series cross sections of the Upper Truckee River were originally surveyed in 1992 with additional surveys in 1994 and 1997 (C. Walck 2003 unpublished data) and had been recently re-surveyed in 2001 (Simon et al. 2003), thus providing a ten-year record of channel changes.

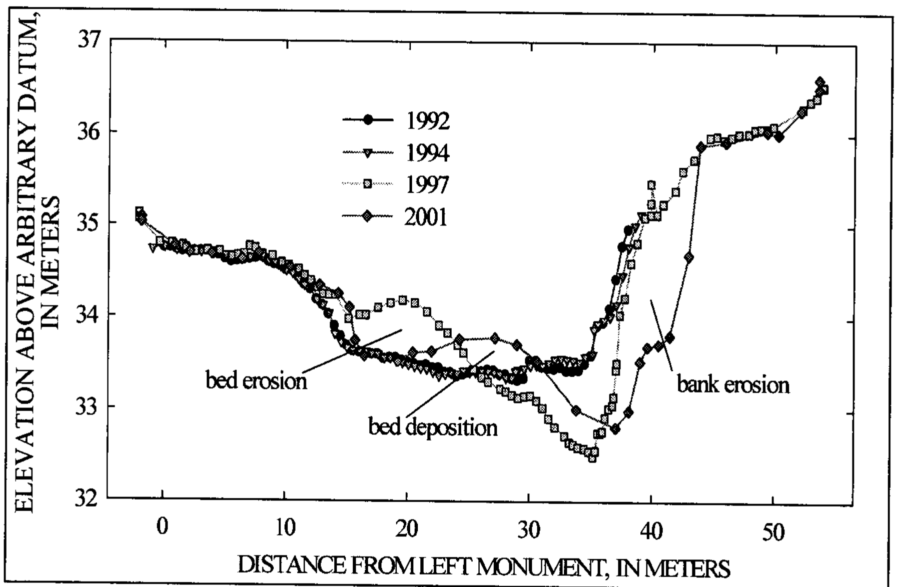

Figure 4-44. Example of overlain surveys from the Upper Truckee River (Simon et al. 2003).

The change in cross-sectional area for a given time period was determined by overlaying time-series cross sections and calculating the area between the channel profiles. The location of the bank toe was determined for the original and 2002 surveyed sections and used to discriminate between erosion and deposition from the bed and banks. Unit rates of streambank erosion were derived from the numerical simulations by: (1) calculating the area eroded in each cross section (the number of cross sections matched for the five streams with available data ranged from 10 for Logan House Creek to 24 for the Upper Truckee River with a mean of 17), (2) taking the average eroded area between successive cross sections, (3) multiplying by the distance between the midpoint of successive cross sections, (4) dividing by the number of years of simulation to obtain a rate in m^3/yr, and (5) dividing by the total reach length to obtain a rate in m^3/yr/km of channel. This provided a unit streambank erosion rate in the same units as those calculated from time-series cross section calculations. The average percentage of fines determined from samples of bank material was multiplied by the volume of material eroded from the channel banks to determine loading rates and yields of fine-grained materials delivered by streambank erosion. Because fines were not found in measurable quantities on streambeds, bed erosion was assumed not to be a contributor of fine sediments.

Reconnaissance Surveys of Stream Channel Stability

From September through November 2002, Simon et al. (2003) identified unstable reaches contributing fine-grained sediment via bank erosion based on reconnaissance surveys of geomorphic conditions along Blackwood, Edgewood, Logan House, Incline, General and Ward Creeks and the Upper Truckee River. The stream channels were assessed based on direct field evidence of stream stability trends throughout each of the watersheds. Evaluations were carried out through field reconnaissance surveys of each main-stem channel. Typically, the lower 80 percent of the main channel length was covered during each survey. At approximate 100 meter intervals, notes and photographs were taken to document eroding reaches and assess their potential for supplying fine sediment. The levels of erosion were divided into four classes: (1) none to negligible, (2) low, (3) moderate and (4) high. The classes were determined through an objective evaluation based on bank height ratio, length of bank instability, vegetation root density, and relative amount of fine-grained materials in the channel bed. The eroding reaches for each stream were then tabulated and mapped to show bank erosion "hotspots" and overall geomorphic trends along the channel. These data were combined with geomorphic data derived from rapid geomorphic assessments (RGAs) of point locations that were conducted not only along the seven intensely studied streams, but throughout the entire basin.

Rapid Geomorphic Assessments

To determine the relative stability and stage of channel evolution for sites in the Lake Tahoe basin, RGAs were conducted throughout the basin at 304 specific locations on a total of 63 streams (Figure 4-45).

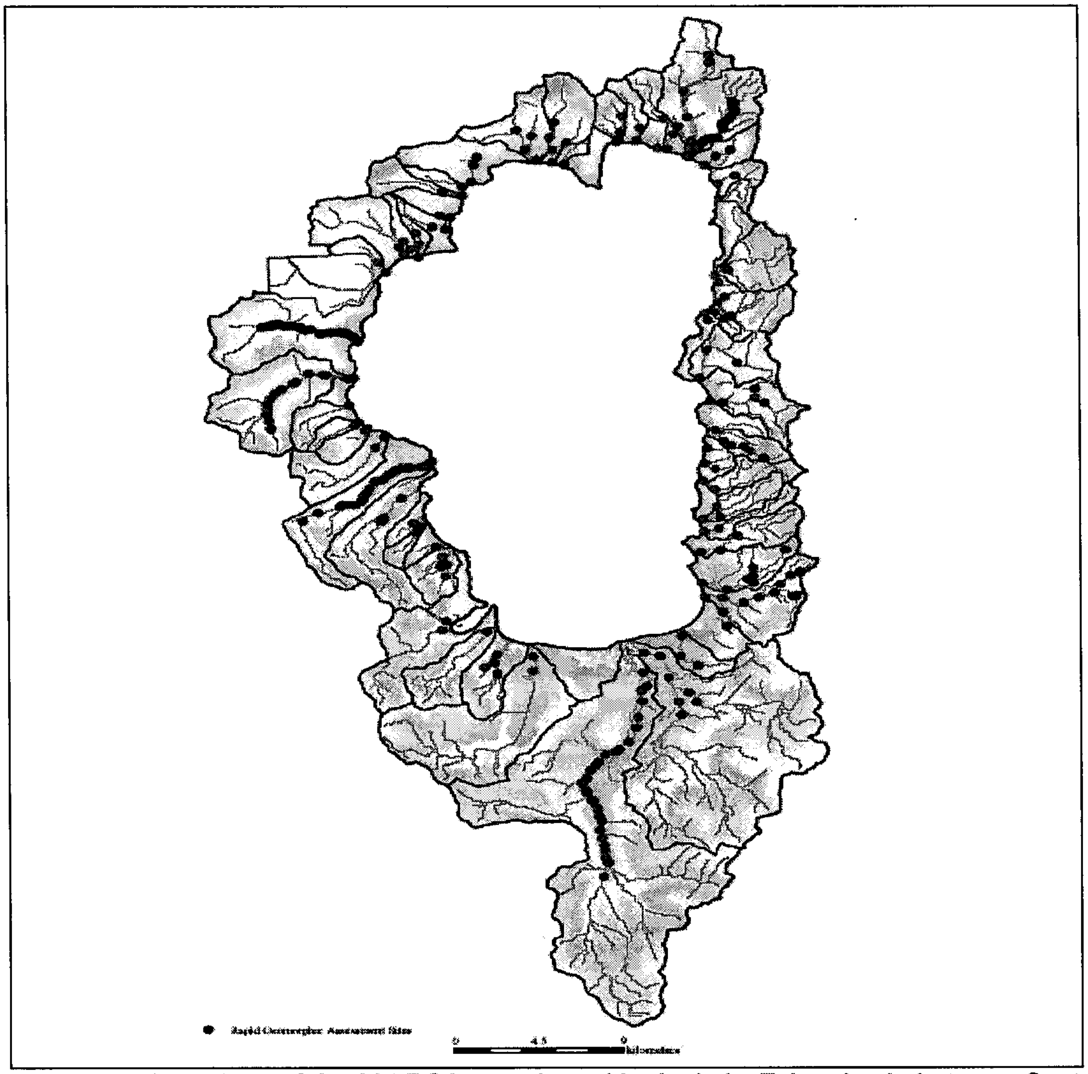

Figure 4-45. Locations of the 304 RGAs conducted in the Lake Tahoe basin between September and November 2002 (Simon 2006).

RGA techniques utilize diagnostic criteria of channel form/conditions to infer dominant channel processes and the general magnitude of channel instabilities. The RGA procedure for sites in the Lake Tahoe basin consisted of three steps; (1) take photographs looking upstream, downstream and across the reach, (2) take samples of bed and bank material for particle size distribution analysis, and (3) make quasi-quantitative assessment of channel conditions based on diagnostic criteria (Simon et al. 2003). This approach has been used successfully in a variety of physiographic environments to rapidly determine system-wide geomorphic conditions of large fluvial networks (Simon et al. 2003). Because they provide information on dominant channel processes rather than only channel form, they can be used to identify disturbances and critical areas of erosion and deposition.

Numerical Modeling

Numerical simulations of upland and channel processes using the AnnAGNPS watershed simulation model (Cronshey and Theurer 1998) and CONCEPTS (Langendoen 2000), respectively, were carried out on three representative watersheds comprising General and Ward Creeks and the Upper Truckee River. The models were used to determine the relative contributions of sediment from upland and channel sources; simulate the effects of the January 1997 runoff event on future sediment loads; and evaluate 50-year trends in suspended sediment delivery to Lake Tahoe from the three watersheds. Each module provides information needed by other modules to enhance the predictive capabilities of each. AnnAGNPS is used to supply the upland sediment load, while CONCEPTS is used to simulate in-stream sediment loading.

AnnAGNPS is a watershed-scale, continuous-simulation, pollutant loading computer model designed to quantify and identify the source of pollutant loadings anywhere in the watershed for optimization and risk analysis. CONCEPTS is a set of stream network, corridor, and water quality computer models designed to predict and quantify the effects of bank erosion and failures, bank mass wasting, bed aggradation and degradation, burial and re-entrainment of contaminants, and streamside riparian vegetation on channel morphology and pollutant loadings.

Basin-Wide Evaluations

Without the resources to conduct detailed numerical simulations of channel processes for each individual stream, as was done for the Upper Truckee River, Ward Creek, and General Creek, a combination of empirical methods were used to estimate channel erosion for the remaining streams. Determination of fine-sediment (< 63 μm) loadings (metric ton/year) was straightforward for the LTIMP streams with historical flow and concentration data. However, estimating fine-sediment loadings from streams with no historical monitoring information required the development of an extrapolation methodology. Simon (2006) developed an extrapolation methodology based upon measured and simulated rates of streambank erosion, the average percentage of fines in the channel banks, diagnostic information obtained from the RGAs, and the bank-stability index (I_B) that represents the percent of reach length with failing banks. A summary of the methods and results from Simon (2006) are provided below.

Extrapolation of Measured and Simulated Streambank Erosion Rates

In general, the technique to estimate basin-wide fine-sediment contributions from streambank erosion relied on extrapolating rates of streambank erosion obtained from time-series measurements of monumented cross sections and from numerical simulations with the CONCEPTS channel evolution model (Nolan and Hill 1991, Simon et al. 2003, Simon 2006).

To obtain the rate of streambank erosion of fine sediment (< 63 μm) from the measured and simulated unit erosion rates for total sediment, values were multiplied by the average percentage of silt-clay in the channel banks. The resulting rates of streambank erosion are expressed in m^3/yr/km of fines (< 63 μm) and listed in Table 4-42.

Table 4-42. Measured and simulated average annual rates of streambank erosion for index streams.

Stream	Bank Composition (% < 63 μm)[a]	Erosion Rate (m^3/yr/km)	Type of Data	Source of Data
Blackwood Creek	5.6	12.2	Measured	Simon et al. 2003
Edgewood Creek	4.9	0.09	Measured	Nolan and Hill 1991
General Creek	7.4	0.92	Simulated	Simon et al. 2003
Logan House Creek	-	0.002	Measured	Nolan and Hill 1991
Upper Truckee River	9.5	9.50	Simulated	Simon et al. 2003
Ward Creek	10.4	4.40	Simulated	Simon et al. 2003

[a]**Data from Simon et al. 2003**

To extrapolate this limited data set to the entire Lake Tahoe basin, diagnostic information obtained during the RGAs was used. Results from the RGA analysis described above, evaluated relative bank instability as the percentage (longitudinally) of each side of the channel that has experienced recent mass failure. Observed conditions ranged from 0 percent (stable banks) to 100 percent (where the entire reach contained failing streambanks). Each bank was assigned a numerical value based on the extent of failures. This value was termed the bank-stability index (I_B). The index attempts to synthesize more quantitative evaluations of streambank stability that might include parameters such as bank height, bank angle, geotechnical strength, and bank-toe erodibility. A summary of all field data and the average I_B values for each stream can be found in Simon (2006).

Relationship between Bank-Stability Index and Streambank Erosion Rate

With an average bank-stability index (I_B) available for each stream, a relationship between this parameter and streambank erosion rates was required for extrapolation to streams without measured data. Using data from the six streams with measured or simulated data (Table 4-42), a regression was performed using a sigmoidal 3-parameter equation based on the general shape of the relation (Simon 2006). Equation 2 (R^2=0.99) and the relation between average, annual streambank erosion rates are expressed in Figure 4-46.

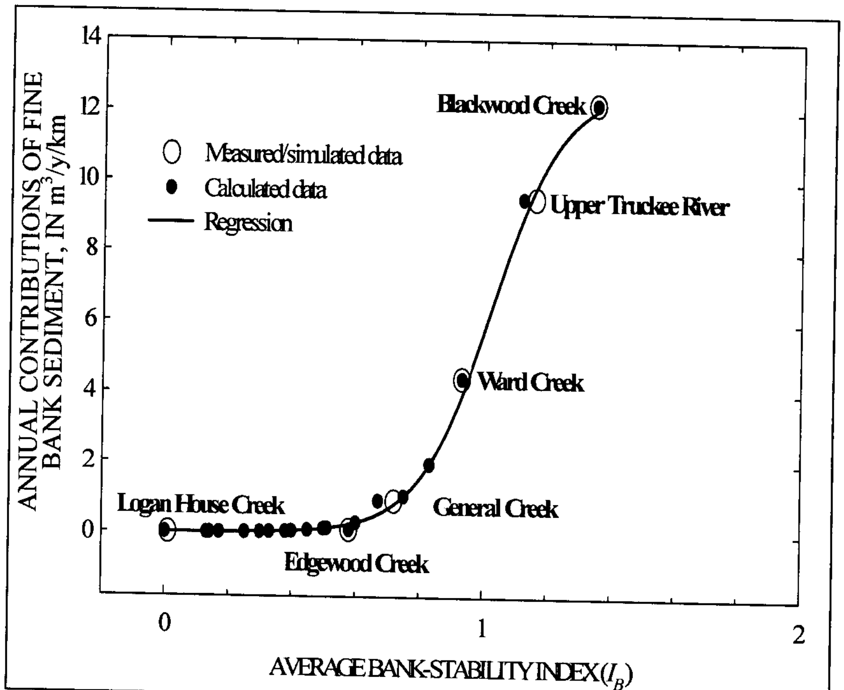

Figure 4-46. Three-parameter sigmoidal equation and the Relation between average, annual streambank erosion rates and average bank-stability index (I_B) (Simon 2006).

$$E_r = \frac{12.6939}{1+e^{-\frac{(I_B-1.0217)}{0.1129}}}$$ **Equation 2**

Where:

E_r = erosion rate of fine (< 63μm) bank sediment in m^3/y/km of channel
I_B = average bank–stability index (percent of reach length with failing banks).

An erosion rate for each stream channel was obtained by substituting the stream's bank stability index value into the above regression equation to provide an average annual erosion rate of fine sediment per unit length of channel. The average annual loading of streambank erosion for each stream was then determined by multiplying this value by the total length of main channels.

Basin-Wide Estimate of Fine-Sediment Loading from Streambank Erosion

Using the above procedures, average annual erosion and delivery of fine sediment to Lake Tahoe were calculated for each stream. (Table 4-42 and Figure 4-47). Specific values for each stream are presented in Simon (2006). Summing the values calculated for each of the 63 watersheds gives an annual average of 1,305 metric tons/year of fine sediment delivered to Lake Tahoe from streambank erosion. The three largest contributors of fine streambank sediment are the Upper Truckee River (639 metric tons/year), Blackwood Creek (431 metric tons/year) and Ward Creek (104 metric tons/year) (Simon 2006).

According to Simon (2006), about 25 percent of the fine sediment delivered to the lake from upland sources (not including the flow coming directly to the lake from intervening zones) emanates from streambank erosion when compared to the calculated total fine sediment loadings. About 22 percent of all fine sediment delivered to Lake Tahoe from upland sources comes from the banks of the Upper Truckee River, Blackwood Creek and Ward Creek (Figure 4-34 and Figure 4-35).

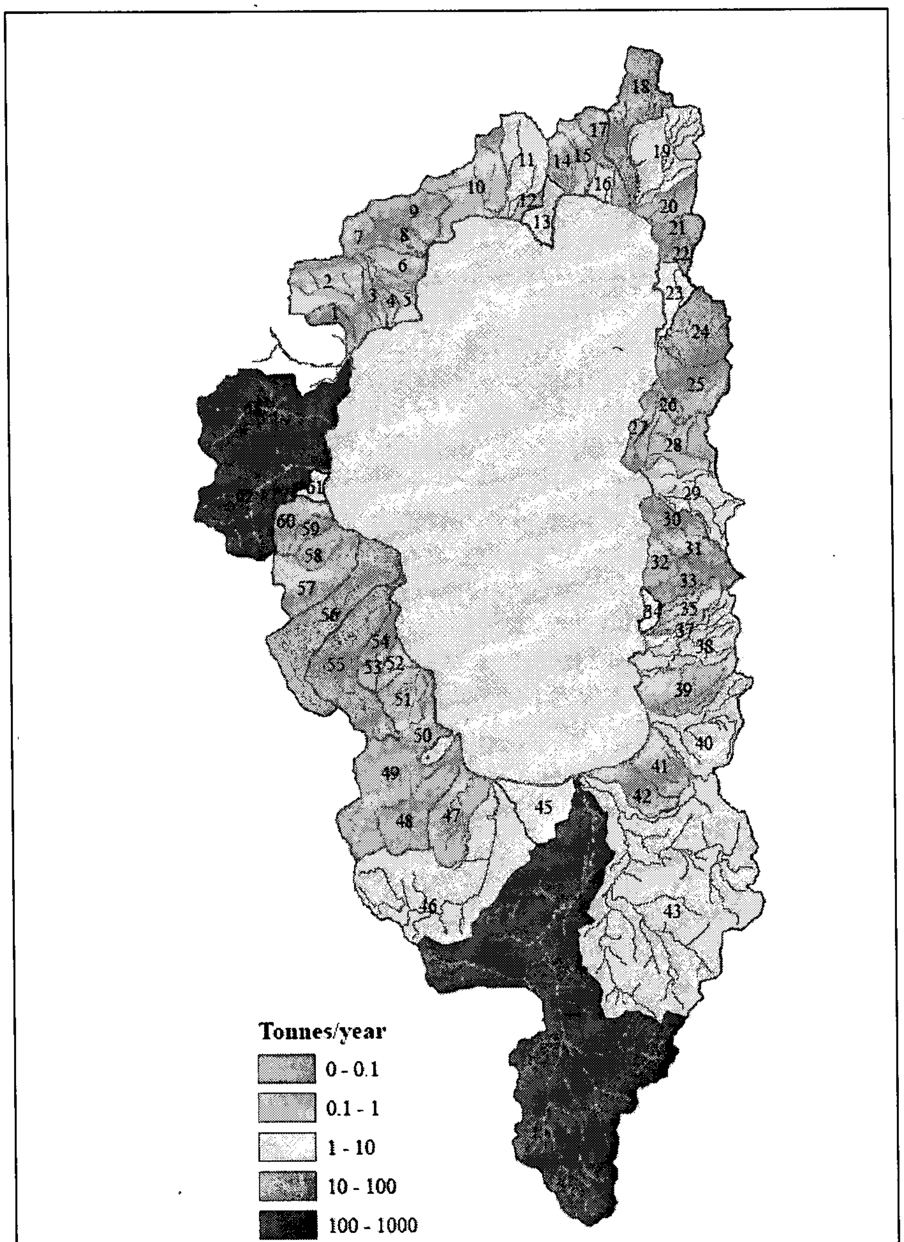

Figure 4-47. Loadings of fine sediment (< 63 μm) from streambank erosion (gray shading indicates no data available; note: tonnes is referred to as metric tons in this report) (Simon 2006).

Refer to Section 4.3 on upland sources and particularly to Section 4.3.5 on sediment loads for a specific discussion as to how these values for stream channel sediment (mass of material < 63 µm) were modified for application within the Lake Tahoe Watershed Model. Channel fines < 63 µm were estimated using the Lake Tahoe Watershed Model to be 3,800 metric tons per year based on calibration to actual LTIMP monitoring data.

Estimates of Nutrient Loading Associated with Streambank Erosion

In addition to the soil particles delivered to stream flow by channel erosion, phosphorus and nitrogen may also accompany this eroded material. To estimate the phosphorus load contributed from stream channel erosion, data from the Ferguson and Qualls (2005) and Ferguson (2005) bioavailable phosphorus study were used. As part of that work, the authors analyzed samples of composite stream channel sediment from areas considered potentially erodable (Simon et al. 2003, R. Wells 2003 personal communication). Samples of these representative, composite samples were taken from nine LTIMP streams (all monitored tributaries except Logan House) and were chemically analyzed for total phosphorus. Results ranged from 0.075 – 0.199 µg total phosphorus/mg sediment (< 63 µm) with a mean of 0.153 µg total phosphorus/mg sediment and a 95 percent confidence interval of 0.096 – 0.197 µg total phosphorus/mg sediment (< 63 µm). This mean value was applied to all streams and was multiplied by sediment load from channel erosion to obtain phosphorus loading. Based on the fine-sediment load of 3,800 metric tons/year from stream channels obtained from the Lake Tahoe Watershed Model, this yielded a total phosphorus load of 0.6 metric tons/year. For the purpose of this evaluation, it was assumed that nitrogen loading from stream channel erosion was proportional to the ratio of stream load-phosphorus to stream load-nitrogen from upland runoff. This yielded a stream channel total nitrogen load of approximately 2 metric tons/year. While the uncertainty of this estimation is high, it only accounts for less than one percent of the total nitrogen budget from all sources. Therefore, the potential error associated with this estimate is negligible.

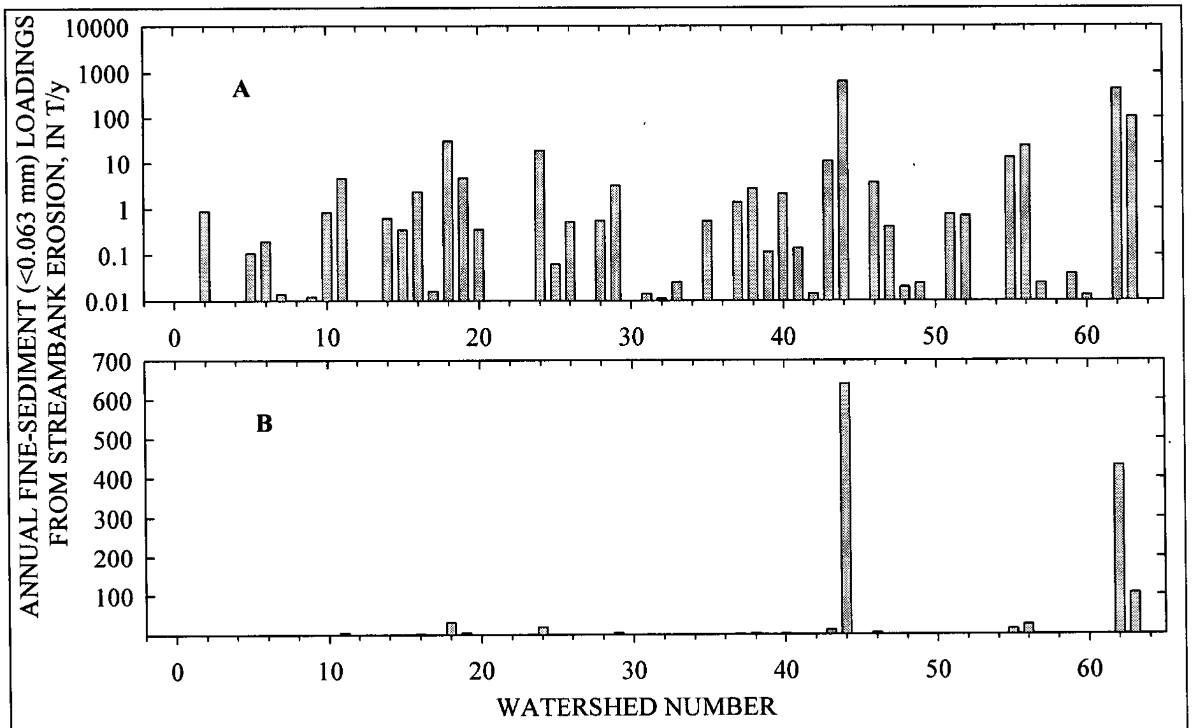

Figure 4-48. Annual, fine-sediment (0.063 mm) loadings in metric tons per year from streambank erosion plotted with log scale (A) and arithmetic scale (B). Note the relatively large contributions from the Upper Truckee River (#44), Blackwood Creek (#62), and Ward Creek (#63). Watershed numbers correspond with Figure 4-47 (Simon et al. 2006).

4.5 Atmospheric Deposition

4.5.1 Overview

Because of the large surface area of the lake (501 km^2) in comparison to its drainage area (812 km^2), it is not unreasonable to expect that loading of nutrients and particulate matter directly to the surface waters of Lake Tahoe through the process of atmospheric deposition loading might be important. For the purpose of discussion, atmospheric deposition only refers to dry fallout or precipitation (as rain or snow) that lands on the lake surface directly. Nutrients and particulate matter deposited over the land portion of the drainage basin may or may not enter Lake Tahoe depending on uptake by vegetation, sequestration within the soil layers, etc. Pollutants that fall onto the land are included in the evaluation of groundwater and upland loading. That is, it was considered beyond the scope of the source category analysis to distinguish between atmospheric sources and land-based sources when considering loading from surface runoff. In particular, the sediment and nutrient content in runoff is different by nature than that of atmospheric deposition – it changes dramatically as rain or snowmelt travels over the landscape as it accumulates pollutants from soil erosion and urbanized land-uses. Furthermore, pollutants that either (1) enter the surface runoff by atmospheric deposition, or (2) are entrained into the atmosphere from the terrestrial environment require land-based controls.

The first comprehensive estimate of the contribution by atmospheric deposition of nitrogen and phosphorus to the annual nutrient budget of Lake Tahoe was made by Jassby et al. (1994). This study analyzed atmospheric deposition from both wet (rain and snow) and dry fallout in comparison to loading from stream inflow. This was the first published research to conclude that atmospheric deposition provides a majority of the dissolved inorganic nitrogen (DIN; defined as nitrate plus ammonium) and total nitrogen to the annual nutrient load of Lake Tahoe. It was further concluded that atmospheric deposition also contributes significant amounts of soluble reactive phosphorus (SRP) and total phosphorus loading, but to a lesser extent than nitrogen.

Reuter et al. (2003) used the data from Jassby et al. (1994) to estimate total nitrogen and total phosphorus loading directly to Lake Tahoe via atmospheric deposition. The resulting loading rates were approximately 230 metric tons per year for total nitrogen and 12 metric tons per year for total phosphorus. Atmospheric deposition of total nitrogen accounted for nearly 60 percent of the nitrogen budget while total phosphorus accounted for 25 – 30 percent of the phosphorus budget. While measurements of the chemical content of atmospheric deposition were assumed to be accurate, there were acknowledged uncertainties associated with extrapolating to the whole-lake surface from a limited sampling network.

In 1999, a cooperative effort began between the TRPA and scientists at UC Davis and the Desert Research Institute (DRI), which resulted in publication of the *Lake Tahoe Air Quality Research Scoping Document* (Cliff et al. 2000). As part of this investigation, it was hypothesized that phosphorus present in wet and dry fallout could have resulted from local sources, i.e. road dust and aeolian (wind) transport from disturbed land, as well as wood smoke (fires in the forest and wood stove use). This agreed with the conclusions of Jassby